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PILOT SCALE INVESTIGATION OF COMPUTERIZED CONTROL OF THE ACTIVATED SLUDGE PROCESS

by

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Report SCAT-12

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This project was carried out under contract for the Policy Development and Research Sector, Canada Mortgage and Housing Corporation, through a grant provided under Part V of the National Housing Act.

This report has been reviewed by Canada Mortgage and Housing Corporation and Environment Canada. The views, conclusions and recommendations expressed herein are those of the authors and do not necessarily reflect the views and policies of either the Corporation or Environment Canada. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

ABSTRACT

A pilot plant evaluation of the feasibility of using on-line instrumentation and an automated data acquisition system to continuously monitor parameters within the activated sludge process is described. Also investigated was the extent to which it is technologically and economically possible to use an automated system to assist the plant operator in controlling the activated sludge process.

Instruments selected for evaluation included sensors for dissolved oxygen, suspended solids, pH, temperature, liquid flow, air flow, and total organic carbon. Sensor precision and accuracy were assessed in comparison to standard reference techniques, and maintenance and calibration requirements were determined. The pilot plant instrumentation was interfaced with a minicomputer data acquisition and control system which was provided with sufficient capacity and peripheral devices to permit activities such as modelling and data analysis.

RÉSUMÉ

Nous décrivons l'évaluation en unité pilote de la faisabilité de l'utilisation d'instruments et d'un système automatisé de saisie des données en direct pour contrôler de façon continue les principaux paramètres du procédé aux boues activées. Nous avons aussi étudié la mesure dans laquelle il est techniquement et économiquement possible d'utiliser un système automatisé pour assister la commande humaine du procédé.

Les instruments retenus pour l'évaluation comprenaient des détecteurs de l'oxygène dissous, des matières en suspension, du carbone organique total et de la température, des débitmètres pour les liquides et l'air et des pH-mètres. Nous avons comparé la précision et l'exactitude de ces instruments par rapport aux techniques normalisées de référence, et déterminé les conditions nécessaires de leur entretien et de leur étalonnage. Les instruments étaient interfacés avec un système de saisie des données et de commande par mini-ordinateur qui était doté d'une capacité suffisante et des périphériques voulus pour permettre des opérations telles que la modélisation et l'analyse des données.

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1 INTRODUCTION

During the past few years many concerns have been expressed about water quality management, and significant efforts have been directed toward improving the operation of wastewater treatment systems to meet more stringent effluent quality criteria. Investigative efforts to define the factors limiting municipal wastewater treatment plant performance recently have received increased attention¹. In these investigations it has been concluded that adequate treatment plant performance and reliability can only be accomplished through the application of effective operational control strategies. Plant design alone does not guarantee good plant performance.

Although the activated sludge process has been in use for many years as the heart of many treatment systems, it has frequently been afflicted with a poor operating record. Nevertheless, the process has maintained its popularity as a treatment alternative. One of the drawbacks contributing to poor plant performance has been the lack of continuous operating records for the major variables used to describe and control process performance²⁻⁵. These variables generally have been measured using intermittent and time-consuming manual sample collection and off-line analysis techniques. Because of the manpower necessary to perform these tasks, the accumulation of continuous operating data is generally restricted to intensive sample surveys and research projects. However, the advent of new and improved on-line continuous monitoring instrumentation suggests that an explosion in the availability of process operating information is occurring.⁶ In the case of the activated sludge process, this information should lead to an improved understanding of the process dynamics and ultimately lead to improved treatment reliability through the application of effective process control strategies^{7,8}.

In November, 1978, the Wastewater Technology Centre (WTC), Environment Canada, embarked on a two-phase pilot plant program funded jointly with the Canada Mortgage and Housing Corporation with the aims of:

- 1) evaluating the feasibility of using on-line continuous monitoring equipment plus an automated data acquisition system for activated sludge process monitoring; and
- 2) determining to what extent it is technologically and economically feasible to use an automated system to assist the plant operator in controlling the activated sludge process.

This report documents the project and outlines the experiences of the WTC using on-line continuous monitoring equipment for data acquisition and control.

2 DESCRIPTION OF PILOT PLANT FACILITY

The pilot plant facility at the WTC consisted of two identical parallel activated sludge units with a common primary clarifier (1.17 m^2 surface area) and independent sludge recirculation systems. A flow schematic is shown in Figure 1. Each biological reactor had a maximum fluid volume of 2.3 m^3 , and provision was made to permit one reactor tank to be divided into a tanks-in-series configuration by the addition of baffles. Fluid volume could be reduced using a manually adjustable outlet weir. During Phase 1 of the project each reactor was operated as a completely stirred tank reactor without baffles.

Upflow circular secondary clarifiers having a surface area of 0.45 m^2 provided solids-liquid separation. Weir height was manually adjustable to permit flexibility in choosing the clarifier fluid volume.

During Phase 1 of the project, one or both of the parallel systems was operated to accomplish the instrument evaluations. Temperature-controlled, degrittied raw sewage from the Burlington Skyway Water Pollution Control Plant was fed to the primary clarifier at a constant flow rate and with normal uncontrolled variations in organic and inorganic concentrations. Primary clarified effluent and return activated sludge were fed to each biological reactor using variable speed pumps, each with a maximum flow of $21.6 \text{ m}^3/\text{d}$. Diffused air was introduced to the biological reactors through perforated PVC piping. Maximum fluid depth was about 1.2 m.

2.1 Instrumentation

Although many instruments have been in laboratory use for many years, to determine, for example, dissolved oxygen, turbidity, temperature, and pH, there has been limited experience to date with their continuous use in the activated sludge process. Process hostility exists in the form of sensor fouling by contaminants in the fluid stream and fouling through the growth of biological films on the sensors. Inevitably, this environment will lead to poor experiences with sensor use if proper considerations for selection, installation, calibration and maintenance are not established.

In the initial stages of this project, the WTC invited instrument suppliers to submit specific instruments for in-house evaluation. The aim of the evaluation was to provide a partial basis for purchase recommendations along with a review of the technical specifications for the various instruments. Instruments tested in this manner included

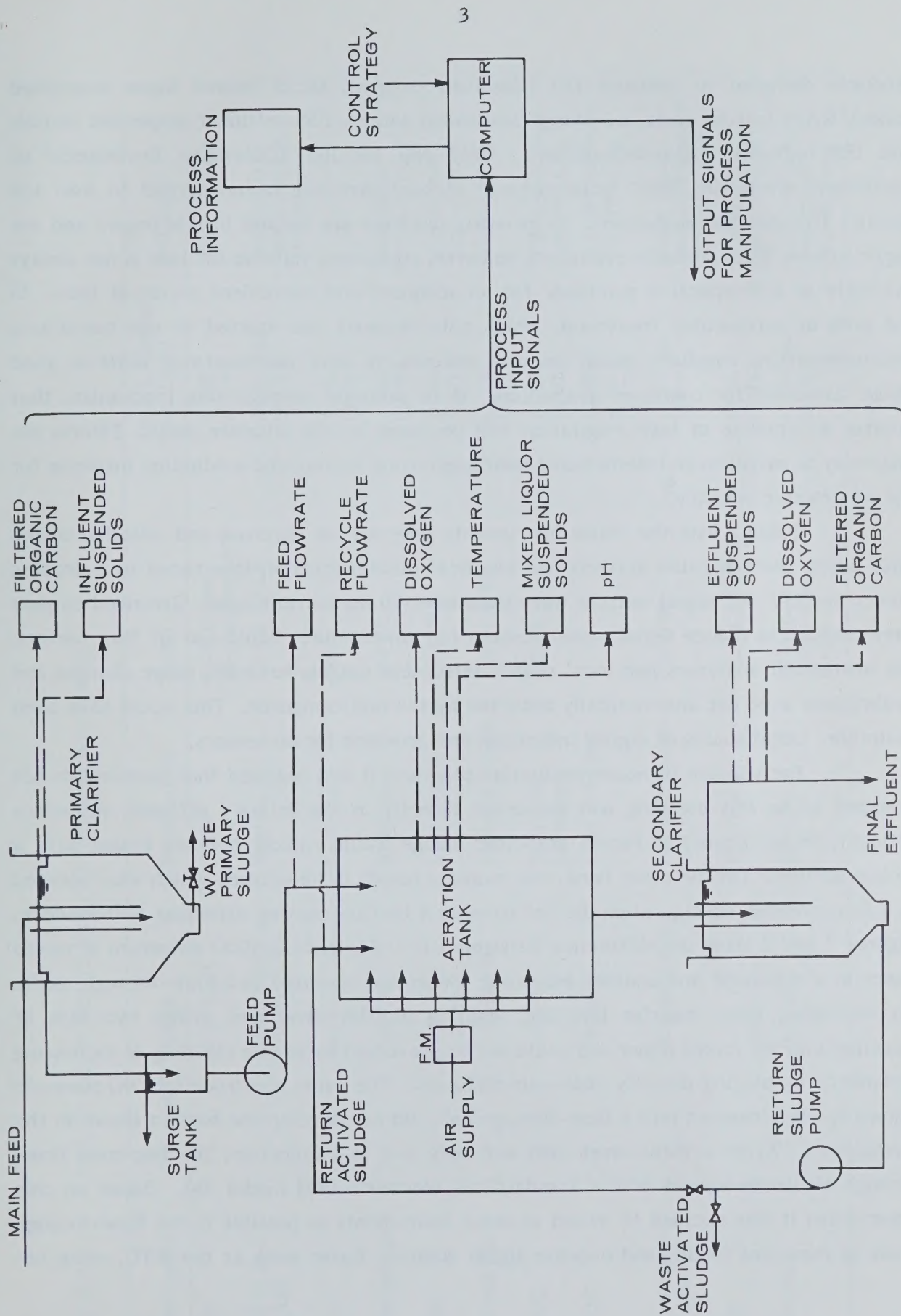


FIGURE 1 ACTIVATED SLUDGE PILOT PLANT - TYPICAL OF TWO PLANTS

products designed to measure DO (dissolved oxygen), MLSS (mixed liquor suspended solids), RASS (return activated sludge suspended solids), ESS (effluent suspended solids), and ISS (influent suspended solids). Only one supplier (Dohrmann Envirotech) of continuous monitoring TOC (total organic carbon) instrumentation agreed to loan the product (DC-62) for evaluation. In general, suppliers are helpful in this regard and are eager to have their products evaluated; however, equipment suitable for loan is not always available to a prospective purchaser for an adequate and convenient period of time. In the area of wastewater treatment, which only recently has started to use continuous instrumentation, suppliers would be well-advised to have demonstrator units in good repair available for customer evaluation. It is partially through this mechanism that greater acceptance of instrumentation will be made by the ultimate users. Efforts are underway to establish an international instrumentation testing and evaluation institute for the wastewater industry⁹.

Table 1 lists the major instruments selected for purchase and installed on the pilot plant. Both parallel systems had identical instrumentation interfaced to a process minicomputer. All signal outputs were isolated 4-20 ma current type. Grounded outputs were avoided to reduce signal noise. Except for temperature, liquid and air flow meters, the instrument analyzers had local switch-selectable ranges; however, range changes and calibrations were not automatically detected by the minicomputer. This would have been desirable. Local analog or digital indication was provided for all sensors.

Early in the in-house evaluation program, it was realized that instruments not designed to be self-cleaning and immersed directly in the primary effluent, secondary effluent, mixed liquor, or return activated sludge would rapidly become fouled with a biological film. On the other hand, one manufacturer's DO electrode which was mounted in a flow-through configuration did not develop a biofilm coating affecting performance. Figures 2 and 3 show the difference between a DO electrode (pHOX) immersed in mixed liquor in a dip-mode and another electrode (Beckman) operated in a flow-through mode. An excessive, mass transfer limiting, reacting biofilm developed within two days of insertion into the mixed liquor and could not be prevented by simple cleaning or increasing turbulence by placing directly above air diffusers. The same electrode (pHOX) shown in Figure 2, when inserted into a flow-through cell, did not develop the biofilm shown in the photograph. After a three-week test and only one re-calibration, the Beckman flow-through electrode agreed with a standardized electrode (YSI model 54). Based on this observation it was decided to mount as many instruments as possible in the flow-through mode to minimize fouling and improve signal quality. Later work at the WTC, using the

TABLE 1 LIST OF INSTRUMENTS AND PARTIAL SPECIFICATIONS

Instrument	Number	Range	Manufacturer	Model	Approx. Capital Cost (Date)	Principle
DO	6	0-20 mg/L	pHOX	65-B sensor 66-transmitter	\$ 4 200 (1978)	flow-through
MLSS & RASS	4	0-300,3000, 30000 mg/L	Monitek	CLAM 52-LE	\$ 5 100 ea. (1978)	photometric, self-cleaning, flow-through
pH	5	0-14	Beckman	980	\$ 5 300 (1978)	
Temperature	1	0-40 °C	Rosemount	444 RL	\$ 400 (1978)	resistance, flow-through
ESS	2	0-30, 100, 300 mg/L	Lisle-Metrix	DRT 285	\$ 1 300 (1978)	photometric, flow-through
Liquid Flow	4	0-45 L/min	Foxboro; Brooks	280 H; 7000	~\$4 000 (1978)	magnetic
TOC	1	variable	Dohrmann- Envirotech	DC-62	\$ 16 000 (1978)	UV -persulphate, infrared CO ₂
TOC	1	variable	Built in-house		\$ 10 000 + labor (1979)	UV -persulphate, infrared CO ₂
Continuous Filter	2	20μ pore size	Astro Resources Corp.	Foxfilter	\$ 1 300 ea. (1979)	paper tape, 20μ pore size for TOC analyser
ISS	1	0-30, 100, 300, 3000 mg/L	Monitek	CLAM 53-LE	\$ 5 300 (1978)	photometric, self-cleaning
Air Flow	2	0-10 L/s	Brooks	3623 meter, 5522H trans- mitter	\$ 1 800 ea. (1978)	rotameter, electronic transmitting

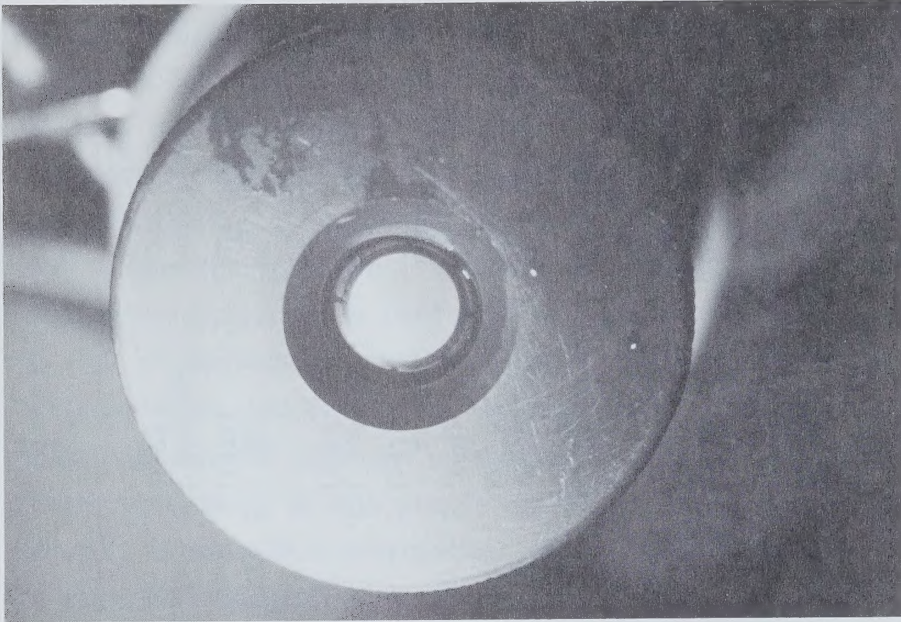


FIGURE 2 pHOX DISSOLVED OXYGEN SENSOR MEMBRANE,
DIP-TYPE

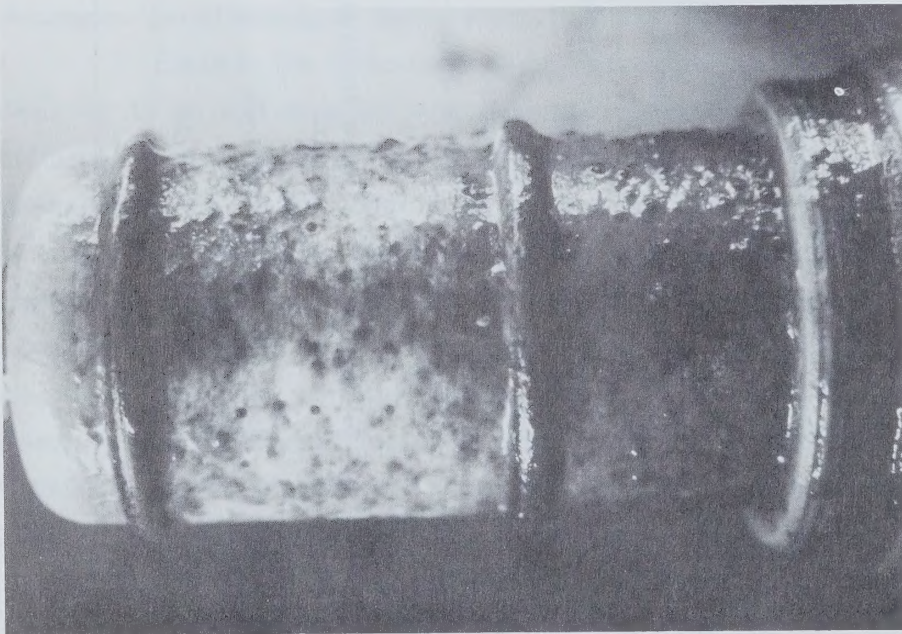


FIGURE 3 BECKMAN DISSOLVED OXYGEN SENSOR MEMBRANE,
FLOW-THROUGH CELL

ERRATUM

Report SCAT-12 Pilot Scale Investigation of Computerized
Control of the Activated Sludge Process

Page 6 The two photos on this page are out of order,
i.e., Figure 2 is actually the photo labelled
Figure 3, and vice versa.

pHOX electrode in a dip mode in a package plant, did not lead to a significant biofilm growth on the membrane. This may have been due to greater shear in the package plant system.

2.2 Digital Minicomputer Hardware

The minicomputer consisted of a Hewlett-Packard (HP) 1000 model 31 computer system (21MX E Series) with the RTE-IVB operating system. The installation is depicted in Figures 4 and 5. The CPU and mass storage devices consisted of 160 K-words partitioned memory, 120M-byte disc, and nine-track 1600 BPI magnetic tape. Operator interface was made using four CRT's, one having graphics capability. Multiple terminals were provided for other users of the computer hardware. Hardcopy was obtained using a 180 character per second printer and a graphics plotter.

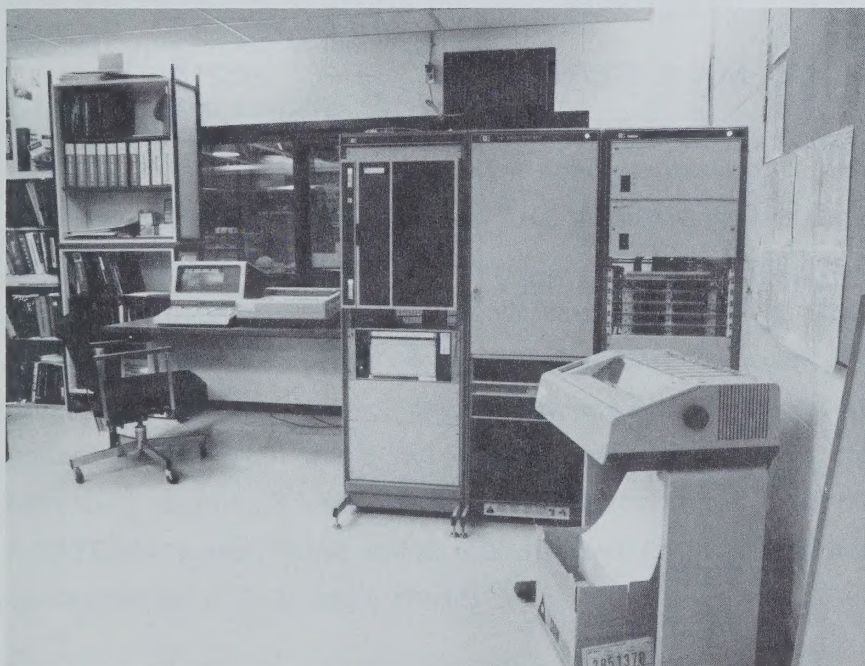
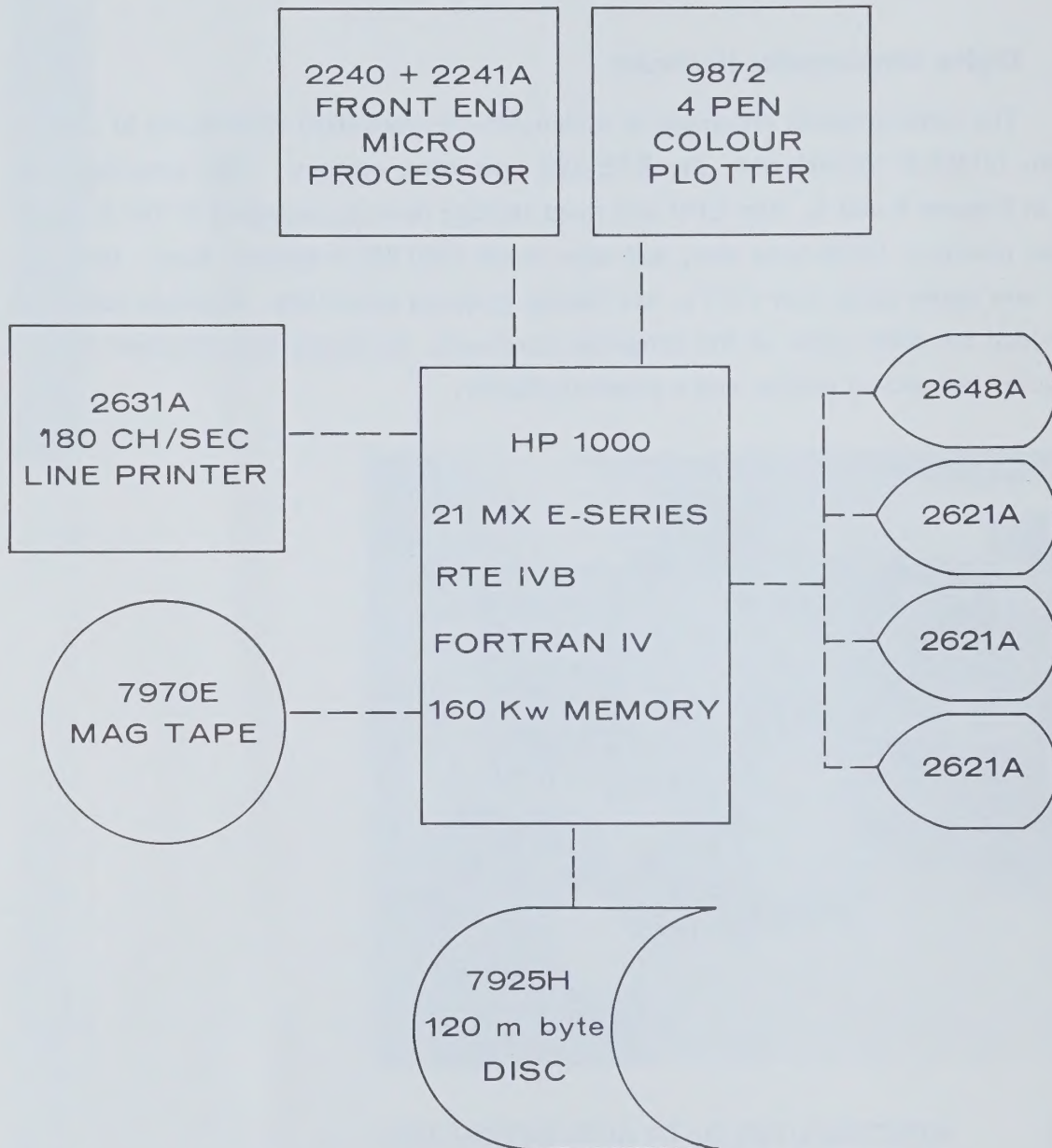


FIGURE 4 MINICOMPUTER DATA ACQUISITION AND CONTROL SYSTEM

Pilot plant instruments were interfaced to the minicomputer via an HP 2240A and 2241A frontend microprocessor. The microprocessor was configured for 32 differential 12-bit analog input (AI) channels (2-10 V), 16 analog output (AO) channels (0-10 V), 16 interrupt channels, 64 digital output (DO) and 32 digital input (DI) channels. Appropriate



* ALL HARDWARE MANUFACTURED BY HEWLETT PACKARD

FIGURE 5 BLOCK DIAGRAM REPRESENTING MINICOMPUTER DATA ACQUISITION AND CONTROL SYSTEM

signal conditioning (e.g., current to voltage, voltage to current) and relay output hardware were associated with the microprocessor. Twisted-pair, shielded cable including a drain wire and screw terminations was used to connect instruments to the signal conditioning hardware. Electrical noise was inhibited and cable was protected between microprocessor and pilot plant by enclosure in an aluminum conduit. The shielded drain wire was grounded at the signal source.

All instruments were connected to the AI channels. Optical isolation was used. Output signals to pumps and certain valves were made through the AO channels. On-off pilot plant devices such as solenoid valves and alarms were interfaced via the DO channels.

The minicomputer was provided with sufficient capacity and peripheral devices to permit activities such as modelling and data analysis. These activities were over and above the activities normally associated with data acquisition and control, thus necessitating an expanded system.

2.3 Minicomputer Software

All user-written software for automatic data acquisition and process control was provided using FORTRAN IV. Real-time extensions provided for continuous sequencing of program activity round-the-clock. These extensions required the learning and use of additional programming commands associated with program scheduling and execution, communication between FORTRAN programs, between FORTRAN programs and the process sensors and control devices via the HP 2240, and storage of the automatically collected data from the FORTRAN program to the mass storage devices. Most of the necessary commands were specific to the HP system. A simplified example of the type of FORTRAN request using an HP real-time extension is given below for a DO measurement calibrated for a 0-20 mg/L range:

```
C
C  READ FROM THE HP2240 (LOGICAL UNIT NO.16) ONE ANALOG INPUT
C  VOLTAGE AND STORE IN THE INTEGER VARIABLE "ISIG".
C
C  FORMAT STATEMENT NO. 5 MEANS "MEASURE ANALOG INPUT
C  STARTING AT SLOT NO.1 AND CHANNEL NO. 2 AND CONTINUE
C  SEQUENTIALLY FOR 1 CHANNEL".
C
```

```

        WRITE (16,5)
5      FORMAT ("AI,1,2,I")
        READ (16,*) ICOND, ISIG
C
C      TEST THE ERROR CONDITION CODE RETURNED IN "ICOND" TO SEE IF THE
C      REQUEST COMPLETED WITHOUT ERROR i.e. 0 = no error
C                                     1 = error or erroneous data
C
        IF (ICOND. EQ. 1) GO TO 100
C
C      CONVERT ANALOG VOLTAGE TO THE CORRECT ENGINEERING UNITS
C      ASSUMING
C      4-20 mAMPS = 2-10 volts AND INSTRUMENT SCALE = 0-20 units
C
        SLOPE=8./20.
        ENG = FLOAT (ISIG-2000)/(SLOPE *1000.0)

100     CALL ERR (ICOND), ERROR RECOVERY ROUTINE.

```

The voltage read (ISIG) was converted to scientific units within the FORTRAN program using a calibration subroutine. Calibration curves were determined for each instrument and the appropriate data (e.g., slope and intercept for linear instrument output) input to the program by the plant operator. If, in the above example, a dissolved oxygen signal was monitored and the concentration was linearly related to voltage as shown in Figure 6, then the voltage would be returned in ISIG as, say, 6 V. Using the stored value of ISIG the FORTRAN program calculated the DO using the linear expression shown in Figure 6. The calculated value was used for monitoring and control purposes in a repetitive manner as required.

In practise, software development to accomplish long-term report generation and process control functions was more involved than the simple example shown above. At least one full-time person-year was necessary to maintain, develop, and operate the hardware and software associated with the minicomputer for the type of investigative

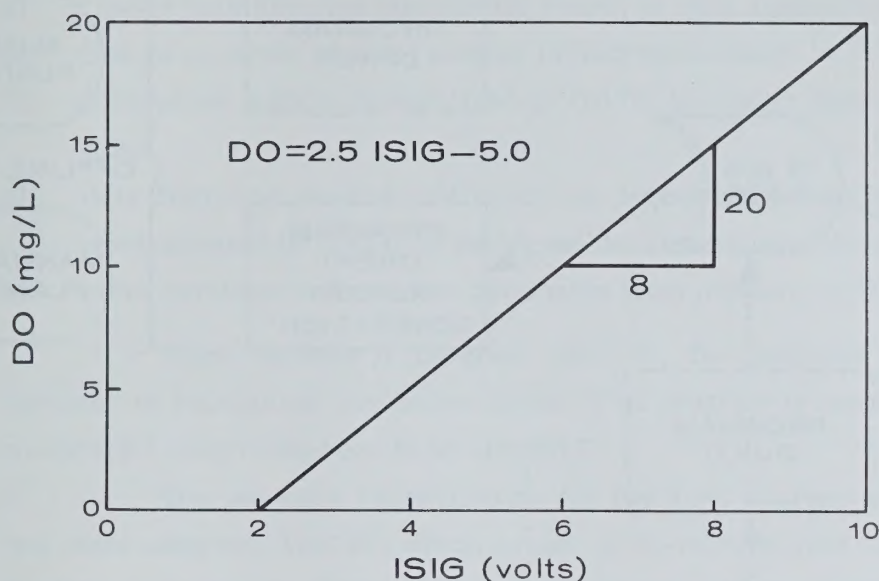


FIGURE 6 RELATIONSHIP BETWEEN CONCENTRATION AND VOLTAGE MEASUREMENTS

work reported here. Program debugging and maintenance were important and time-consuming functions. The operator had to have a knowledge of the minicomputer operating system, digital arithmetic, real-time programming, and of FORTRAN IV or a similar language. It also was a very significant advantage to have a minicomputer operator experienced in the operation of the pilot plant.

2.4 Data Acquisition and Report Generation Software

For data acquisition and report generation, several programs were written and disc files created. Figure 7 summarizes the information flow path of these programs and files.

Program DATU was the principal program involved in on-line data acquisition from the pilot plant sensors. Program DATU was scheduled to run once every five seconds, requesting and obtaining a millivolt reading from each of 32 analog instrument input channels. After one minute had elapsed, the 12 readings for each sensor were averaged, converted from voltages to scientific units, and written to an on-line "circular" file. The data were time-stamped with the Julian day and the minute. DATU also scanned the system memory to check several items alterable by the user:

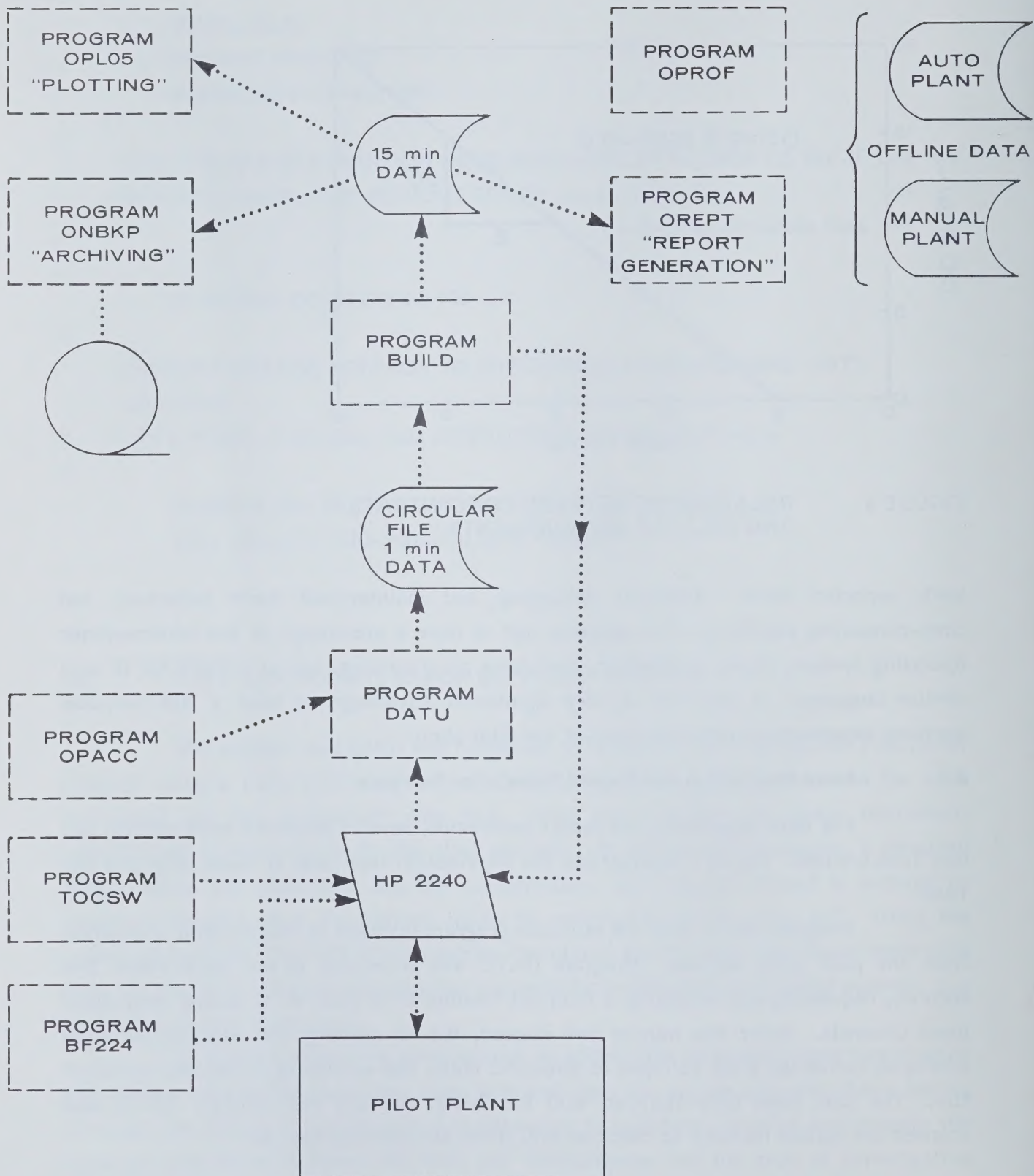


FIGURE 7

SCHEMATIC OF DATA ACQUISITION, REPORT GENERATION AND CONTROL SOFTWARE STRUCTURE

- a) change in calibration constant(s), range, or data acquisition rate for any sensor;
- b) change in sensor channel number in microprocessor;
- c) calibration notices transmitted to DATU to inhibit data acquisition during calibrations;
- d) data from one on-line TOC analyzer sequentially monitoring two effluent streams were assessed by DATU to decide on the stream identification;
- e) other pertinent information obtainable from memory by DATU.

When necessary, program OPACC, for operator access, was run by the operator to manipulate the above items. This program presented a menu to the operator on the CRT which could easily be altered.

The sequence identification for the TOC analysis was governed by a separate real-time program, TOCSW, which cycled at 30-minute intervals. This program automatically controlled the TOC analyser feed stream, alternatively providing flow from each system by manipulating a three-way solenoid valve using the digital output devices. The cycle time was governed by the response characteristic of the TOC analyzer.

On-line data were stored only temporarily in the circular file. If desired, these data were used for special purposes. The file was self-limiting in size to conserve disc space; thus, program BUILD was scheduled to run on a 15-minute cycle to read new data entered into the circular file by DATU, to calculate the 15-minute averages of these data, to time-stamp the data, and to write the time and averages to a larger disc file on a long-term basis (e.g., 30 days). Based on the on-line measurements of liquid flow, air flow, temperature, DO and MLSS, program BUILD also calculated the oxygen uptake rate (OUR) and specific oxygen uptake rate (SCOUR) of the microorganisms in the aeration tank. Off-line measurements of the volumetric oxygen transfer coefficient ($K_L a$) and aeration tank volume were provided to permit calculation of OUR and SCOUR. Program BUILD provided round-the-clock alarm capability for gross instrument failure or out of limit conditions.

Off-line data for laboratory analyses such as COD, BOD₅, TKN, NH₃-N, were entered for a specific date and time via the CRT's to two disc files. Each of these files accommodated data from one of the parallel pilot plant systems. Operator-collected data for sludge volume index (SVI), gravimetrically determined MLSS and RASS, clarifier blanket height, effluent SS and manually determined solids retention time (SRT) values were accommodated in these files.

There were four separate methods of obtaining soft or hardcopy outputs of the on-line and off-line data. These methods included:

- 1) Listing of each 15-minute average for on-line data from program BUILD between times specified by the operator using program ONBKP.
- 2) Graphic plotting of on-line data for any 24-hour period using program OPLO5.
- 3) Listing of off-line data between times specified by the operator using program OPROF.
- 4) Tabulation in a summary format of off-line and on-line data for any 24-hour period using program OREPT. This tabulation consisted of mean, and 15-minute minimum and maximum values for each variable. Other pertinent variables, such as organic loadings, clarifier solids loadings, and clarifier surface loadings, were also calculated and printed.

Program ONBKP permitted the on-line file storing the 15-minute averages to be stored on magnetic tape. This action was necessary to backup the data in the event of a disc failure and for long-term data storage. FORTRAN programs were also backed up on magnetic tape.

Program BF224 was a special purpose program which permitted the pilot plant operator to obtain direct millivolt readings from the HP 2240 and 2241 AI channels. These readings were used to compare on-line sensor results with standard measurement techniques for instrument evaluation and calibration.

Provision was made for the pilot plant operator to log comments regarding plant operation on a disc file dedicated to this function. This gave a permanent record of pertinent events surrounding plant operation and an auxilliary location for data which could not be managed by the other programs and files. A print-out of this information was easily obtained by specifying the dates of interest.

3 INSTRUMENT EVALUATION

After the selection of the process sensors, a program was initiated to monitor long-term instrument response under process conditions. The objectives of this evaluation were:

- a) to assess instrument precision and accuracy compared to standard reference techniques,
- b) to determine maintenance requirements,
- c) to determine calibration requirements.

These evaluations were necessary to verify instrument suitability for on-line data collection in field practice. The instrumentation reliability was important in the application of process control strategies.

To determine on-line instrument precision and accuracy, a program was initiated to collect data to permit statistical comparison to a standard reference technique. Table 2 summarizes the minimum frequency of data collection for comparative purposes.

TABLE 2 MINIMUM DATA COLLECTION FREQUENCY FOR INSTRUMENT EVALUATION

Instrument (manufacturer)	Frequency (per week)
MLSS (Monitek)	2
RASS (Monitek)	2
DO (pHOX)	2
ESS (Lisle-Metrix)	2
ISS (Monitek)	2
pH (Beckman)	1
Temp (Rosemount)	1
Liquid Flow (Brooks, Foxboro)	1

3.1 Dissolved Oxygen

In aerobic biological wastewater systems, one aim is to convert organic carbon to CO_2 and new bacterial cells. In nitrifying systems there is the added objective of converting ammonia nitrogen to nitrate nitrogen. These objectives require the biochemical use of oxygen. In activated sludge systems, the oxygen needed is usually provided by compressors with submerged diffusers or by mechanical surface aerators. Usually a minimum of 1 to 2 mg/L of dissolved oxygen is considered necessary to promote biological activity and guarantee process performance. Aeration requires the most significant single input of energy in a majority of systems. This has a significant effect on plant operating costs and in many cases consumes most of the utility budget. Thus minimization of oxygen consumption will minimize energy costs associated with aeration. Control of the DO to minimize energy consumption may also lead to improved process performance.

A 1977 survey¹⁰ including 30 conventional activated sludge plants in Ontario indicated that annual utility requirements comprised an average of 21% of the total operating costs or 58% of the total supplies and equipment costs. Using this data and assuming that a 20% utility saving can be made through DO control, an annual 4.3% saving in total operating costs would be realized, or an annual 11.5% saving in the total supplies and equipment expenses. For these 30 plants this would amount to a total dollar saving of \$414 500 per year or an average \$13 820 per year per plant. Actual plant savings would vary with scale. Assuming a capital investment of \$10 000 per plant¹¹ a pay back period (PBP) can be calculated:

$$\begin{aligned}
 \text{PBP} &= \frac{\text{investment cost \$}}{\text{\$ savings per year}} \\
 &= \frac{\$ 10\,000}{\$ 13\,820/\text{yr}} \\
 &= 0.72 \text{ years}
 \end{aligned}$$

It can be assumed that the equipment has at least a ten-year life span. The initial investment would seem to be so highly profitable as to suggest inaccuracy in the simplistic estimation of investment cost or annual savings. Annual increases in energy costs since 1977 and future increases in energy costs will favour DO control strategies, including implementation in smaller plants.

Implementation of DO control requires that a suitable sensor exist for on-line process measurement of DO. Figures 8a, 8b and 8c show the correlation of three independent on-line DO analyzers (pHOX) to a laboratory calibrated YSI Model 54 oxygen analyzer. Two probes were located in one of the parallel pilot plant reactors while one was located in the other reactor. Table 3 summarizes the performance of the individual sensors. A paired t-test was used to evaluate the significance of divergence of the pHOX data from the standard YSI data.

TABLE 3 DO SENSOR PERFORMANCE

Sensor	Number of Data Points (n)	Duration of Assessment (months)	Mean Difference* (mg/L)	Significantly Different from zero
1	72	8	-0.12	Yes
2	43	7	-0.02	No
3	53	5	+0.03	No

* based on paired t-test at 95% level.

These data showed that the instrument deviated from the standard YSI reference electrode in one of the three cases; however, the mean difference was relatively small and barely significant in this case.

The error standard deviations for the DO sensors were evaluated using the paired data. Table 4 summarizes the results based on a reference electrode having a standard deviation, S_r , of 0.05 mg/L. This standard deviation has been indicated as the most likely value obtainable for most commercially available membrane systems⁹. Instrument standard deviation was determined using:

$$S_I = \sqrt{\frac{2}{S_M^2 - S_R^2}}$$

where:

S_I = calculated instrument standard deviation

S_M = measured standard deviation of differences

S_R = reference sensor standard deviation.

These estimates of instrument precision were conservative since relatively high precision was allocated to the reference YSI electrode in each case.

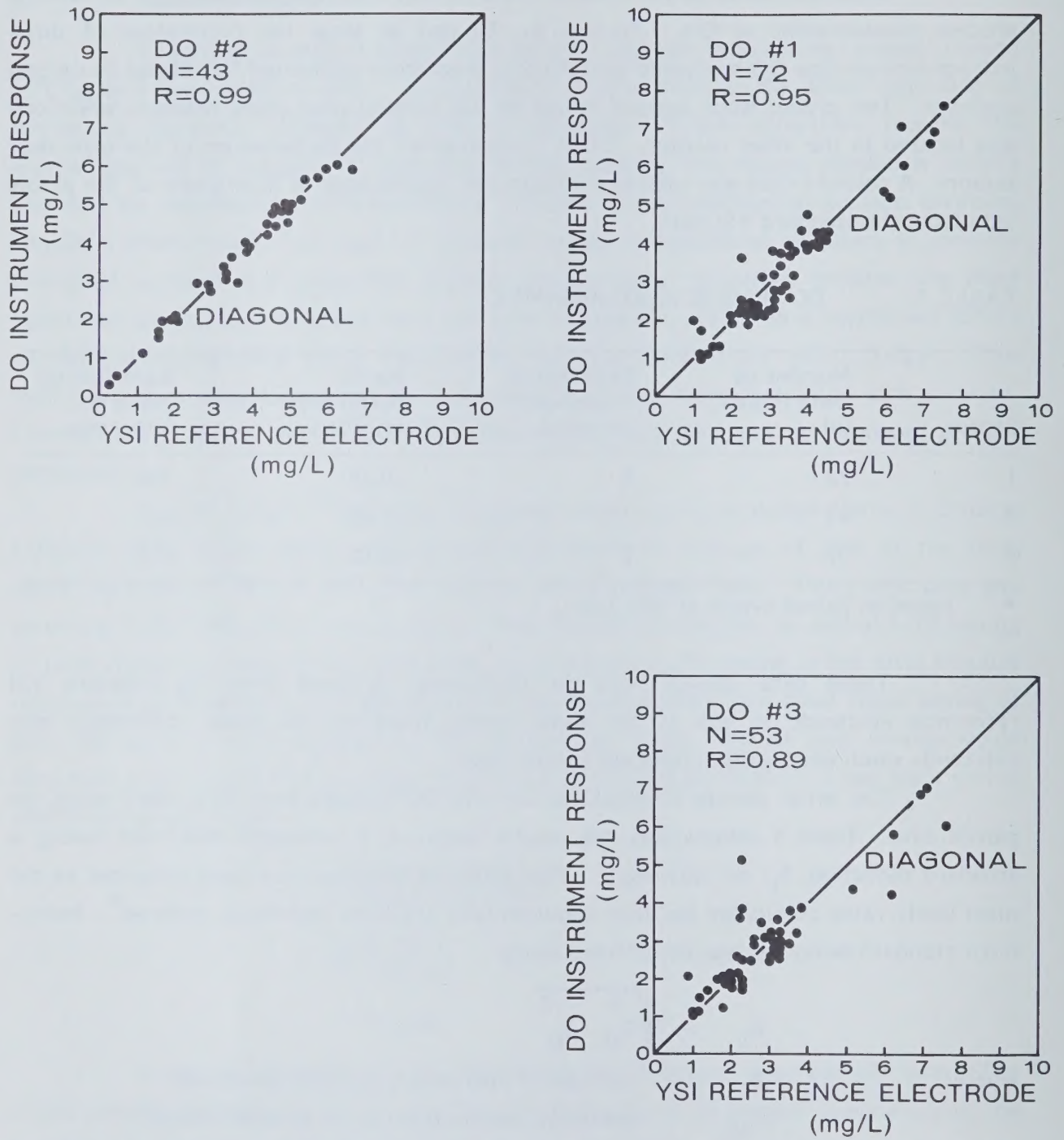


FIGURE 8 RELATIONSHIP BETWEEN DO INSTRUMENT RESPONSE AND
REFERENCE ELECTRODE

A lower instrument standard deviation, S_I , can be expected as S_R is increased to a value corresponding to that of S_I . Having made this assumption, Sørensen⁷ evaluated DO sensors statistically and measured S_I values averaging about one-half of those reported in Table 4.

TABLE 4 DO INSTRUMENT STANDARD DEVIATIONS

Sensor	n	Standard Deviation (mg/L)	
		S_R^*	S_I
1	72	0.05	0.43
2	43	0.05	0.21
3	53	0.05	0.70

* from reference 12.

Irrespective of the analysis method, in typical usage these instruments do not meet the specifications of 1% of scale discrimination or 0.5% accuracy as stipulated by the manufacturer. It is stressed, however, that the sensors are generally reliable and acceptable for on-line process monitoring and control.

Table 5 lists the maintenance and calibration requirements for the three pHOX DO sensors discussed. In general, problems were not identified until pHOX electrode response readings had deviated from the reading of a standardized YSI check probe immersed in the mixed liquor or the electrode response became erratic. The plug-in pHOX electrode cell was exchangeable on a replacement part exchange basis with a guarantee of one year. It is essential for a plant to stock exchange cells for unexpected failures. One important observation made at the WTC was that the manufacturer supplied new electrodes packaged in an bisulphite solution to eliminate dissolved oxygen in the storage cell. In fact, this solution was observed to have the characteristic odour of H_2S after several months' storage. It was believed that the H_2S was attacking the membrane-covered silver cathode. Subsequently the sulphite solution was replaced with distilled water for storage.

In the pilot plant aeration system it also was found to be necessary to locate the suction tube of the centrifugal pumps feeding the electrode to avoid pumping entrained air from the diffusers past the electrode. Entrained air lead to a noisy signal

TABLE 5 MAINTENANCE AND CALIBRATION REQUIREMENTS FOR pHOX DO SENSORS

Date (1979)	Problem	Action
Jan. 11	Inconsistent performance	Sensors 1 and 2 replaced
22	Low response to high D.O. (>5)	Sensor 3 recalibrated
23	Inconsistent performance	Sensor 2 replaced
Feb. 1	Low response to high D.O. (>7)	Sensor 3 recalibrated
5	Low response to high D.O. (6.5)	Sensor 3 recalibrated
Apr. 8	Membrane partially fouled	Sensor 1 recalibrated
9	Adjusted as per YSI after recalibration	Sensor 1 adjusted
June 9	Erratic, recirculation pumps unreliable	Sensor 3 replaced
18	Transmitter/probe jumps to full scale	Sensor 3 switched off for duration of tests
Aug. 28	Drifting signal	Sensor 1 calibration adjustment
Sept. 3	Didn't match reference YSI probe	Sensors 1 and 2 calibration adjustment
10	Partially fouled, increased flow to cell	Sensor 2 membrane cleaned
12	Readjustment after previous cleaning	Sensor 2 calibration adjustment
16	Erratic performance	Sensors 1 and 2 membranes replaced and recalibrated
17	Wouldn't span	Sensor 1 replaced
Oct. 15	Increased full scale adjustment wouldn't span for K_{La} test	Sensor 2 recalibrated

from the probe. In full-scale systems both probe location and number of probes will be important factors in accurately and precisely determining DO concentration. It will be very important to have rapid transfer of mixed liquor to a probe to minimize oxygen uptake in transit in a flow-through cell.

It was demonstrated in re-aeration tests that the pHOX electrode did not respond as quickly to the de-aeration phase as a YSI probe with smaller electrode, electrolyte capacity, and 0.025 mm membrane thickness versus the 0.05 mm thickness of the pHOX membrane. Because of the pHOX electrode size, it is probably inherently less

suited to monitoring rapid disturbances in DO concentration. The advantage of relatively long and stable operation outweigh this disadvantage for control purposes but it must be considered in non-steady state analyses. Further efforts are being directed to measurement of instrument response at the WTC.

Considering the process information that can be obtained through on-line DO monitoring and the potential for significant energy savings through DO control, the relative ease of operation of DO sensors make them a highly desirable addition to biological wastewater treatment systems. Their usage must be tempered by the recognition that skillful placement, regular attention and maintenance must be applied to ensure energy savings and improved operation.

3.2 Mixed Liquor, Return, and Waste Activated Sludge Suspended Solids

Three important process variables that must be monitored in activated sludge systems are

- a) reactor mixed liquor suspended solids concentration,
- b) return activated sludge suspended solids concentration, and
- c) waste activated sludge suspended solids concentration.

These variables must be monitored to determine process organic loadings, secondary clarifier thickening effectiveness, and the sludge wasting rate for effective plant solids management. Usually, monitoring is carried out manually using solids filtration, drying, and gravimetric determination of the solids concentrations. These manual determinations suffer from delay and are time-consuming and generally limited to occasional grab or composite samples of the appropriate fluid streams. Often, these determinations may be adequate for plant operation but much plant information can be lost through infrequent sampling and analysis. For example, determination of waste sludge quantities can be very difficult in full-scale plants due to large fluctuations in solids concentration, particularly where intermittent wasting interrupts the return sludge flow, subjecting the clarifier to variable loadings. The use of on-line suspended solids monitoring instrumentation potentially can provide continuous records of plant performance and improve the possibility of better operational control.

A Monitek model 52-LE CLAM suspended solids sensor was chosen for measuring suspended solids concentrations in these process streams. Initially, a rapid screening evaluation was made of one sensor located to monitor mixed liquor and another

sensor located to monitor return activated sludge. The objective of this evaluation was to observe the nature of the signal and its precision without interfering with the instrument in a way not quantifiable after the initial calibration. The duration of the evaluation was four weeks.

The meters were independently calibrated off-line by adapting a 5-cm inside diameter opaque hose about 15 cm in length over the end of the sampling shaft. The hose was filled with mixed liquor or return activated sludge of gravimetrically determined suspended solids concentrations. The sample was agitated with a simple plunger. Full scale and zero calibrations were repeated to minimize errors due to interdependence. Zero calibrations were performed using tap water or filtered effluent.

After calibration the sensors were located in the appropriate process streams on the pilot plant. The test consisted of comparing the suspended solids measured using the sensors to suspended solids concentrations measured gravimetrically in grab samples. Four sets of test runs were performed with each set comprising 10 comparisons between the gravimetric and sensor data for a total of 40 measurements. Since the instrument had a damping switch (on/off), and because of the flow-through configuration, the sets were run to include each factor in the assessment as shown in Table 6.

TABLE 6 CONDITIONS FOR EVALUATION OF SUSPENDED SOLIDS SENSORS

	Signal Damping	
	On	Off
Flow Past Sensor	3.4	3.4
(L/min)	6.8	6.8

To estimate the laboratory precision obtainable through manual sampling and gravimetric analysis, duplicate measurements were made on a total of 41 return activated sludge samples and 50 mixed liquor suspended solids samples by the pilot plant operator; the standard deviations for each stream were 81 and 63 mg/L, respectively. These estimates were used as reference values in determining the precision of the sensors according to:

$$S_{\text{Sensor}}^2 = S_M^2 - 2S_R^2$$

where:

$$S_M^2 = \text{measured variance of difference between the gravimetric and sensor suspended solids concentrations,}$$

$$S_R^2 = \text{variance of duplicate laboratory reference measurements,}$$

$$= (0.081 \text{ g/L})^2 \text{ for RAS suspended solids,}$$

$$= (0.063 \text{ g/L})^2 \text{ for MLSS.}$$

Since no acceptable standard of known concentration exists¹² for suspended solids, an estimate of the accuracy of the sensors could not be made. As Sørensen⁷ indicated, the variance of the reference technique must be added to the variance of the instrument response since, in this case, the reference technique is used to calibrate the instrument.

Tables 7 and 8 present the average difference between the 10 paired comparisons and instrument standard deviations, respectively, of the RAS suspended solids sensors.

TABLE 7 MEAN DIFFERENCE BETWEEN GRAVIMETRIC AND SENSOR DATA FOR RAS SUSPENDED SOLIDS

Flow Past Sensor (L/min)	Mean Difference (g/L) with Signal Damping	
	On	Off
3.4	-0.479	-0.403
6.8	-0.311	-0.978

During the tests the average gravimetric RAS suspended solids concentration was 6.26 g/L.

In the case of the high flow rate and no damping for the RAS sensor a significantly higher difference and instrument standard deviation were observed. This set of observations was made after an electronic component of the unit had been repaired

TABLE 8 INSTRUMENT STANDARD DEVIATION FOR RAS SUSPENDED SOLIDS BASED ON PAIRED DATA

Flow Past Sensor (L/min)	Standard Deviation (g/L) with Signal Damping	
	On	Off
3.4	0.21	0.32
6.8	0.39	0.19

without recalibration of the unit and is not representative. Figure 9 is a plot of the pooled data showing the general relationship between instrument and reference data. A re-analysis of the RAS data was performed using the error variance calculated from residual sum of squares after linear regression of the sensor data to the corresponding gravimetric results. This eliminated a significant fraction of the error due to inadequate calibration. The instrument standard deviations calculated using this procedure are overestimated since there is no contribution to error due to the inaccuracy in gravimetric analysis, but the variance due to the gravimetric technique is small compared to the measured variance.

Table 9 summarizes the standard deviation after regression for the four sets of data. It is apparent that a large fraction of the instrument error shown in Table 9 is due to the calibration under the high flow and no damping conditions. It can be concluded based on Tables 8 and 9 that the standard deviation of the Monitek CLAM 52-LE suspended solids sensor yields a representative value between the range 0.19-0.39 g/L for returned activated sludge at a concentration of approximately 6.26 g/L. The same precision could be assumed to hold for waste activated sludge suspended solids. Signal damping and flow manipulation over the range indicated had no discernible effect on signal quality. With calibration adjustment, it subsequently was possible to minimize the differences between the sensor and gravimetric data such that the mean differences were not statistically different from zero.

Similar analyses were performed using the MLSS sensor. Results are tabulated in Tables 10 and 11. In each case, the average difference between gravimetric and sensor results was statistically different based on a paired t-test; however, the average of the

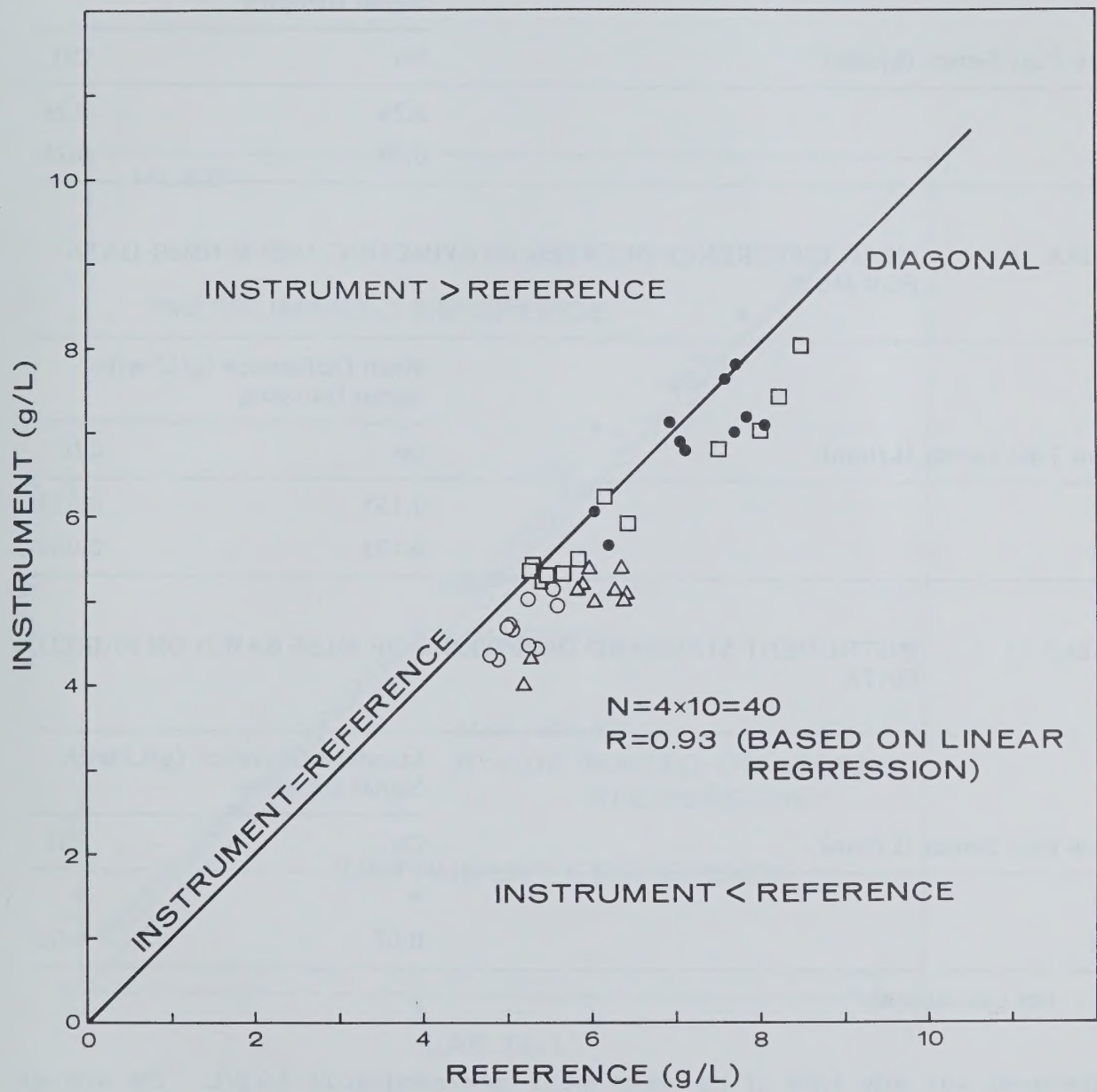


FIGURE 9 SCREENING EVALUATION OF RETURN ACTIVATED SLUDGE
SUSPENDED SOLIDS SENSOR

TABLE 9 INSTRUMENT STANDARD DEVIATION FOR RAS SUSPENDED SOLIDS
BASED ON RESIDUAL SUM OF SQUARES

Flow Past Sensor (L/min)	Standard Deviation (g/L) with Signal Damping	
	On	Off
3.4	0.24	0.26
6.8	0.39	0.28

TABLE 10 MEAN DIFFERENCE BETWEEN GRAVIMETRIC AND SENSOR DATA
FOR MLSS

Flow Past Sensor (L/min)	Mean Difference (g/L) with Signal Damping	
	On	Off
3.4	0.155	0.055
6.8	0.133	0.064

TABLE 11 INSTRUMENT STANDARD DEVIATION FOR MLSS BASED ON PAIRED
DATA

Flow Past Sensor (L/min)	Standard Deviation (g/L) with Signal Damping	
	On	Off
3.4	*	*
6.8	0.07	0.06

* not calculatable

differences was only 3.4% of the mean MLSS concentration of 3.0 g/L. The average standard deviation based on the paired data was 0.07 g/L or 2.3% of the mean. Figure 10 shows the linear relationship between the sensor and the gravimetric data for the four sets of runs pooled together.

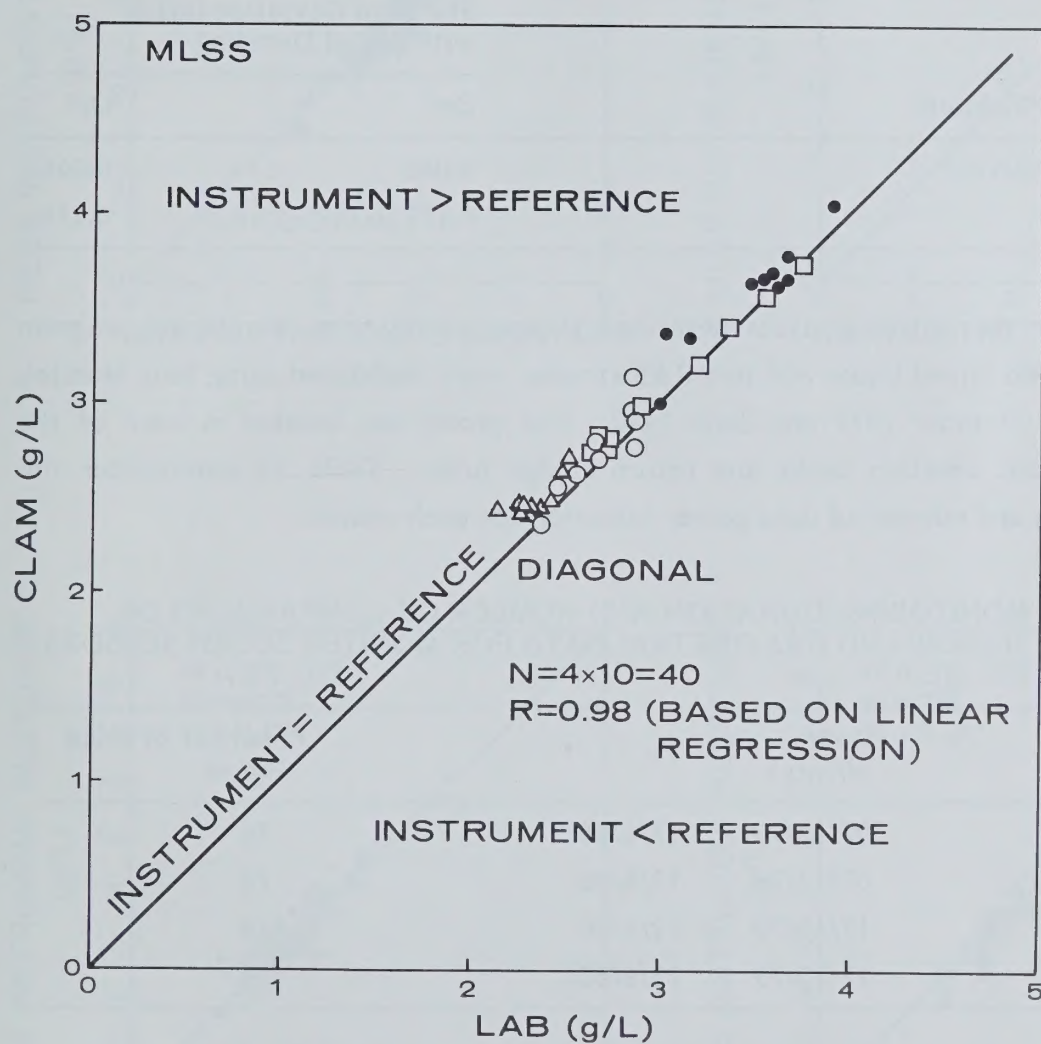


FIGURE 10 SCREENING EVALUATION OF MIXED LIQUOR SUSPENDED SOLIDS SENSOR

The instrument standard deviations of the four sets of runs based on the residual sums of squares after regression are listed in Table 12. The average standard deviation was 0.09 g/L.

TABLE 12 INSTRUMENT STANDARD DEVIATION FOR MLSS BASED ON RESIDUAL SUM OF SQUARES

Flow Past Sensor (L/min)	Standard Deviation (g/L) with Signal Damping	
	On	Off
3.4	0.065	0.044
6.8	0.117	0.116

After the initial analyses described above, a long-term monitoring program was initiated. Two mixed liquor and two RAS streams were monitored using four Monitek sensors between October 1979 and June 1980. One probe was located in each of the parallel pilot plant aeration tanks and return sludge lines. Table 13 summarizes the application dates and number of data points collected for each sensor.

TABLE 13 MONITORING DURATION AND NUMBER OF COMPARISONS OF SENSOR AND GRAVIMETRIC DATA FOR MONITEK SOLIDS SENSORS

Sensor	Date (d/m/y)	Number of Data Points
MLSS no. 2	07/12/79 - 12/6/80	86
RASS no. 2	07/12/79 - 12/6/80	78
MLSS no. 1	17/10/79 - 12/6/80	119
RASS no. 1	17/10/79 - 12/6/80	103

Figure 11 shows the correlation of the sensor data to gravimetric analyses of grab samples. With the exception of the MLSS no. 2 sensor, the correlation coefficients all exceed 0.9. Inspection of the raw data showed the first one-half of the data for the MLSS no. 2 sensor to be consistently higher than the gravimetric data due to inadequate

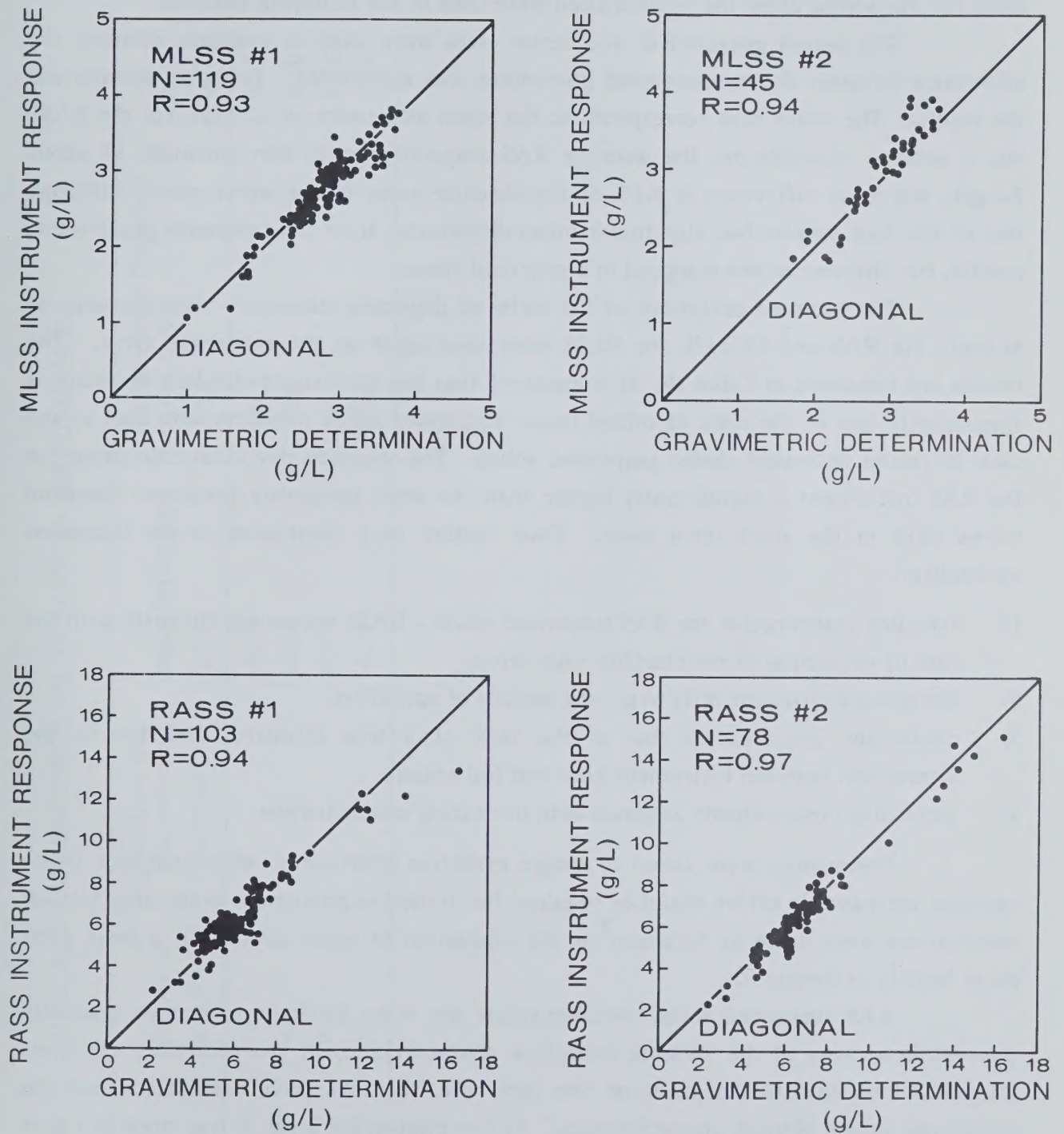


FIGURE 11 RELATIONSHIP BETWEEN SENSOR AND GRAVIMETRIC MIXED LIQUOR AND RETURN ACTIVATED SLUDGE SUSPENDED SOLIDS DATA

calibration. After recalibration, the performance of this sensor matched those of the other three sensors with a relatively high correlation ($r = 0.94$) to the gravimetric results. Data for this sensor after the recalibration were used in the following analyses.

The paired gravimetric and sensor data were used to evaluate whether the difference between the measurement procedures was significant. Table 14 summarizes the results. The worst case corresponds to the mean difference of 0.29 g/L for the RASS no. 2 sensor. Considering the average RAS suspended solids concentration of about 7.0 g/L, the mean difference is 4.1% of the absolute value in the worst case. Although two of the four sensors had significant mean differences from the reference gravimetric results, the differences are marginal in a practical sense.

The standard deviations of the series of duplicate laboratory measurements of 81 mg/L for RAS and 63 mg/L for MLSS were used again as the reference error. The results are tabulated in Table 14. It is apparent that the instrument standard deviation is significantly less in the case of mixed liquor suspended solids measurement than in the case of return activated sludge suspended solids. The standard deviation calculated for the RAS instrument is significantly higher than the level previously predicted based on paired data in the short-term tests. Four factors may contribute to the increased variability:

- 1) sampling inaccuracies for RAS suspended solids - RASS varied significantly with the rate of revolution of the clarifier rake drive;
- 2) increased instrument drift over long periods of operation;
- 3) calibration inaccuracies due to the lack of a true standard, and due to the interaction between instrument zero and full scale;
- 4) increasing measurement variance with increasing concentration.

Precautions were taken to ensure effective instrument calibration, but unacceptable increases in effort would be required for limited improvement in results. Similar observations were made by Sorensen⁷ in his evaluation of solids sensors in a large pilot plant facility in Denmark.

RAS suspended solids concentrations are more difficult to sample manually than MLSS because of the variable underflow characteristics of the secondary clarifier. Underflow concentration depends on the flow rate, the rake drive mechanism, and the sludge and sludge blanket characteristics. At the pilot-scale level it was observed that the rake mechanism had a significant effect on underflow concentration, with solids

TABLE 14 MLSS AND RAS SUSPENDED SOLIDS SENSORS PERFORMANCE

Sensor	Number of Data Points	Duration of Assessment (months)	Mean Difference (g/L)	Significantly Different from zero $P_{0.05}$	S_I (g/L)
MLSS no. 1	119	9	-0.01	No	0.17
MLSS no. 2	45	7	+0.10	Yes	0.20
RASS no. 1	103	9	+0.09	No	0.80
RASS no. 2	78	7	-0.29	Yes	0.58

varying sinusoidally in the same period as the rake drive mechanism (0.5 rpm). Figure 12 shows the variability of the underflow concentration sampled using the HP-1000 minicomputer at a time interval of five seconds. Each peak occurred almost exactly at a two-minute interval in phase with one revolution of the rake drive. A power spectra of the data confirmed the oscillation of the underflow concentration synchronous with the rake drive. The important point was that the RAS solids varied significantly during a short time period, complicating the ability to manually sample the same concentration that the sensor observed. Thus, the 10% relative precision is a conservative estimate of the sensor's performance.

The importance of choosing an appropriate sampling interval is clearly demonstrated by inspection of Figure 12. If a two-minute discrete digital sampling frequency was chosen for this sensor, it would be possible to observe only the peaks or troughs of the underlying continuous record. This is called aliasing and is a potential source of error inherent in all discrete real-time digital signal processing¹³. In the case of this pilot-scale system with the relatively fast rake drive, it would be necessary to sample at least every 30 seconds to recreate the true suspended solids signal in the RAS stream and avoid the aliasing error. Full-scale clarifiers can be expected to behave differently than the pilot-scale clarifier evaluated here. In the full scale, rake speed and blanket characteristics will influence underflow characteristics.

Table 15 summarizes the maintenance and calibration requirements for the four Monitek CLAM 52-LE sensors located in the parallel pilot plant system. These sensors were mechanically reliable units with relatively few repair requirements. It is essential, however, to carry a spare parts inventory to ensure rapid repair to defective units. Significantly more effort was required to maintain instrument calibration than was required for maintenance. The self-cleaning feature of the unit was completely satisfactory, eliminating the need for manual cleaning. Improved calibration and precision would be desirable for this instrument, but the inherent problems in relating photometric measurements to gravimetric measurements will likely work against improved results. It was observed over time that sensors giving satisfactory readings at one level of concentration would not give satisfactory readings at significantly higher or lower concentrations. This necessitated sensor recalibration. Normally, large excursions in mixed liquor suspended solids do not occur rapidly; whereas, return sludge suspended solids can be subject to significant variation due to items such as variable clarifier

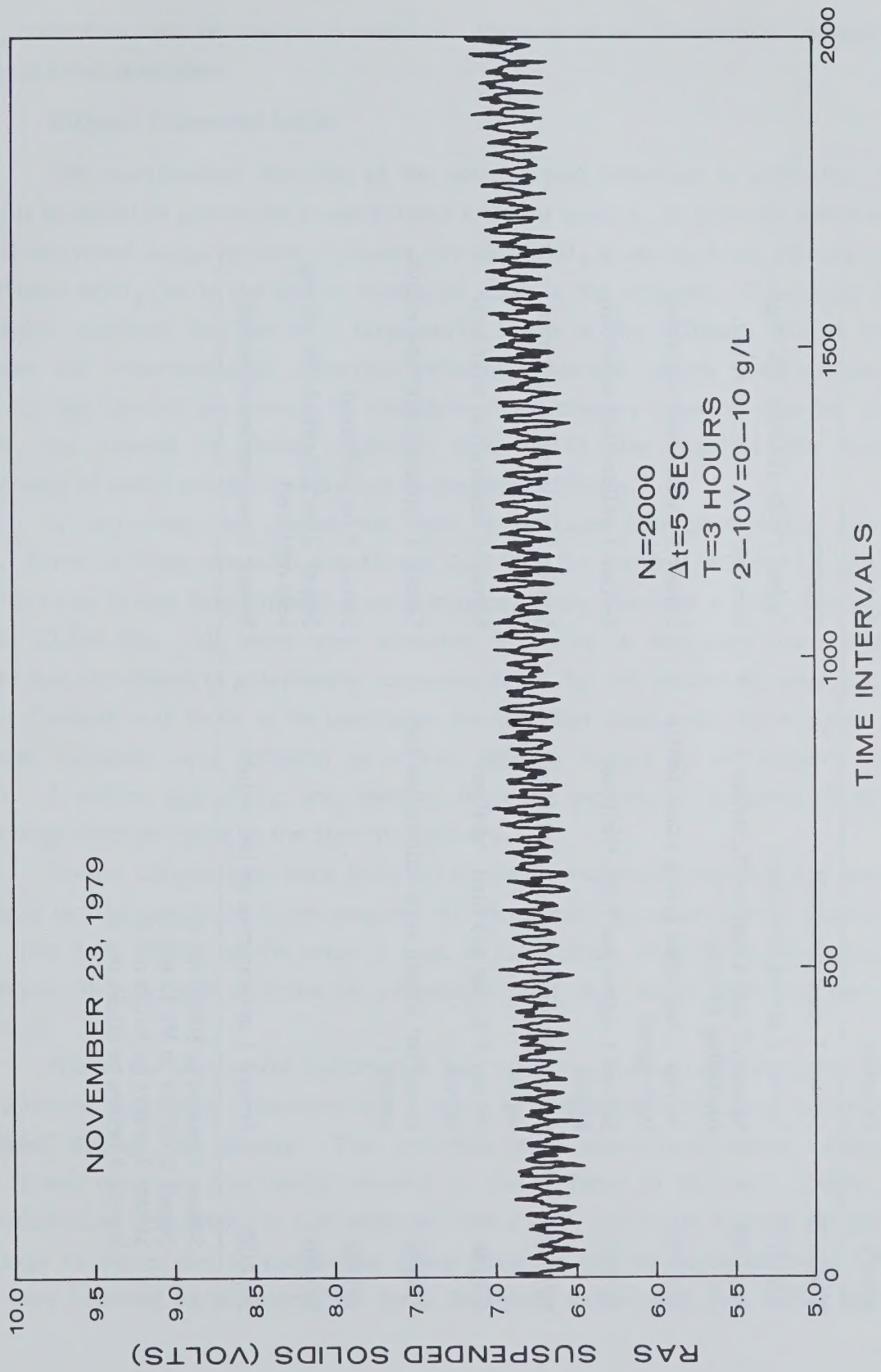


FIGURE 12 VARIABILITY OF CLARIFIER UNDERFLOW CONCENTRATION SAMPLED AT FIVE-SECOND INTERVALS

TABLE 15 MAINTENANCE AND CALIBRATION REQUIREMENTS FOR MONITEK CLAM
52-LE SUSPENDED SOLIDS SENSORS*

Date d/m/y	Problem	Action
24/10/79	Sensor 1 dead photocell	Replaced.
15/11/79	Sensor 2 giving low signal	Adjust calibration by 200 mg/L.
10/3/80	Sensors 2 and 4 "drifted", Sensor 1 beginning to drift	Sensors 1, 2, 4 recalibrated.
24/3/80	Sensor 3 had been giving consistently high signal	Sensor 3 calibration adjusted.
5/5/80	Sensor 1 signal too high, "drifted" signal	Sensor 1 calibration adjusted.
27/5/80	Sensor 4 signal too high, "drifted" signal	Sensor 4 calibration adjusted.
6/6/80	Sensor 4 signal too high, "drifted" signal	Sensor 4 calibration adjusted.
7/7/80	Could not attain zero calibration for sensor 1	Sensor 1 replaced with spare unit.
7/7/80		Sensor 3 recalibrated
7/7/80		Sensor 2 recalibrated and wiping seal replaced.
28/7/80	Sensor 1 inaccurate at low values	Sensor 1 calibration adjusted.

* Sensor 1 refers to RASS no. 1
Sensor 2 refers to MLSS no. 1
Sensor 3 refers to RASS no. 2
Sensor 4 refers to MLSS no. 2

loading, underflow rate, or wasting procedures. Methods of on-line calibration need to be investigated and developed.

3.3 Effluent Suspended Solids

The clarification function of the solids-liquid separator in activated sludge systems is essential to guarantee an acceptable effluent quality. In properly designed and operated activated sludge systems, effluent filtrable BOD_5 is usually a low fraction of the total effluent BOD_5 due to the loss of biological solids in the effluent. The failure of the solids-liquid separator can result in large solids losses in the effluent. These factors emphasize the importance of effective effluent suspended solids measurement for monitoring and control purposes. To complete the necessary mass balance for control purposes, the control of solids retention time (SRT) also requires the accurate measurement of solids unintentionally lost in the plant effluent.

A two-week test period was used to evaluate four photometric turbidity sensors. Three of these sensors (Lisle-Metrix DRT 285, Eur Control MEX2-FAK100, Hach Surface Scatter 5) had flow-through configurations, while one was a self-cleaning unit (Monitek CLAM 53). All units were mounted in series in the pilot plant effluent. Turbidity was correlated to gravimetric suspended solids for the instrument analysis. One unit (Eur Control) was found to be unsuitable for the pilot plant scale since higher flows than those available were required to prevent biofilm fouling on the sensor's optical surfaces. A rotary gear pump was used to feed the sensors. This pump effectively sheared large flocs escaping in the clarifier effluent.

Similar correlations were observed between instrument response and gravimetric results for the remaining three sensors. All three units gave correlation coefficients greater than 0.95. Based on the relative ease of calibration, availability, and price, the Lisle-Metrix DRT 285 was selected for subsequent pilot plant usage after the two-week test period.

The initial instrument calibration was tedious. During calibration the wastewater, initially containing approximately 100 mg/L suspended solids, was continuously recirculated through the sensors. Two problems were experienced during calibration. Firstly, it was observed that solids adhered to the surfaces of the recirculation tank during calibration. Secondly, it was believed that a good possibility existed for particle size change to occur due to continuous pump shear in the recirculation loop. These factors were believed to be responsible for a downward instrument drift during the time

required to stabilize and calibrate the instruments. It was also observed that large changes in full-scale adjustment interacted with the zero adjustment necessitating repetitive readjustment during calibration. For these reasons and to save time during calibration, it was decided to obtain only a linear correlation between instrument and gravimetric results rather than a 1:1 correspondence.

Figure 13 shows the comparison between the DRT 285 sensor and the gravimetric results for the two-week evaluation period. During this period secondary clarifier effluent was pumped through the instrument at a flow rate of 2 L/min. The clarifier was operated under a range of loading and recycle rates to manipulate effluent suspended solids. This manipulation was difficult, but a wide range in process response was observed as shown in Figure 13. Specifically, a linear response with high correlation ($R = 0.96$) was observed between the sensor and the gravimetric results over the two-week period. It is apparent that the data are not distributed about the diagonal. A paired t-test showed a significant difference between the instrument and gravimetric results as was expected due to the calibration procedure.

Instrument precision was determined using the measured residual sum of squares from the linear regression of the data shown in Figure 13. This lead to a calculated value of 3.5 mg/L for instrument standard deviation. This error is within the repeatability specified by the manufacturer. The standard deviation of the gravimetric reference technique was independently determined to be 2.1 mg/L from a set of 118 duplicate measurements during a three-week period in February, 1979.

After the preliminary two-week evaluation period, DRT 285 turbidimeters were installed to monitor the secondary clarifier overflows from each of the parallel pilot plants. Figure 14 shows the results obtained during nine- and seven-month periods for the suspended solids sensors. Table 16 summarizes the results for the longer term evaluation based on paired data and linear regression analysis. The instrument standard deviation for the DRT 285 effluent suspended solids sensors was calculated in three separate ways:

- i) using the laboratory-determined reference standard deviation of 2.1 mg/L;
- ii) using a reference standard deviation of 5.2 mg/L determined from Standard Methods¹² Section 208 D; and
- iii) using the residual variance calculated after linearly relating the instrument data to the gravimetric results.

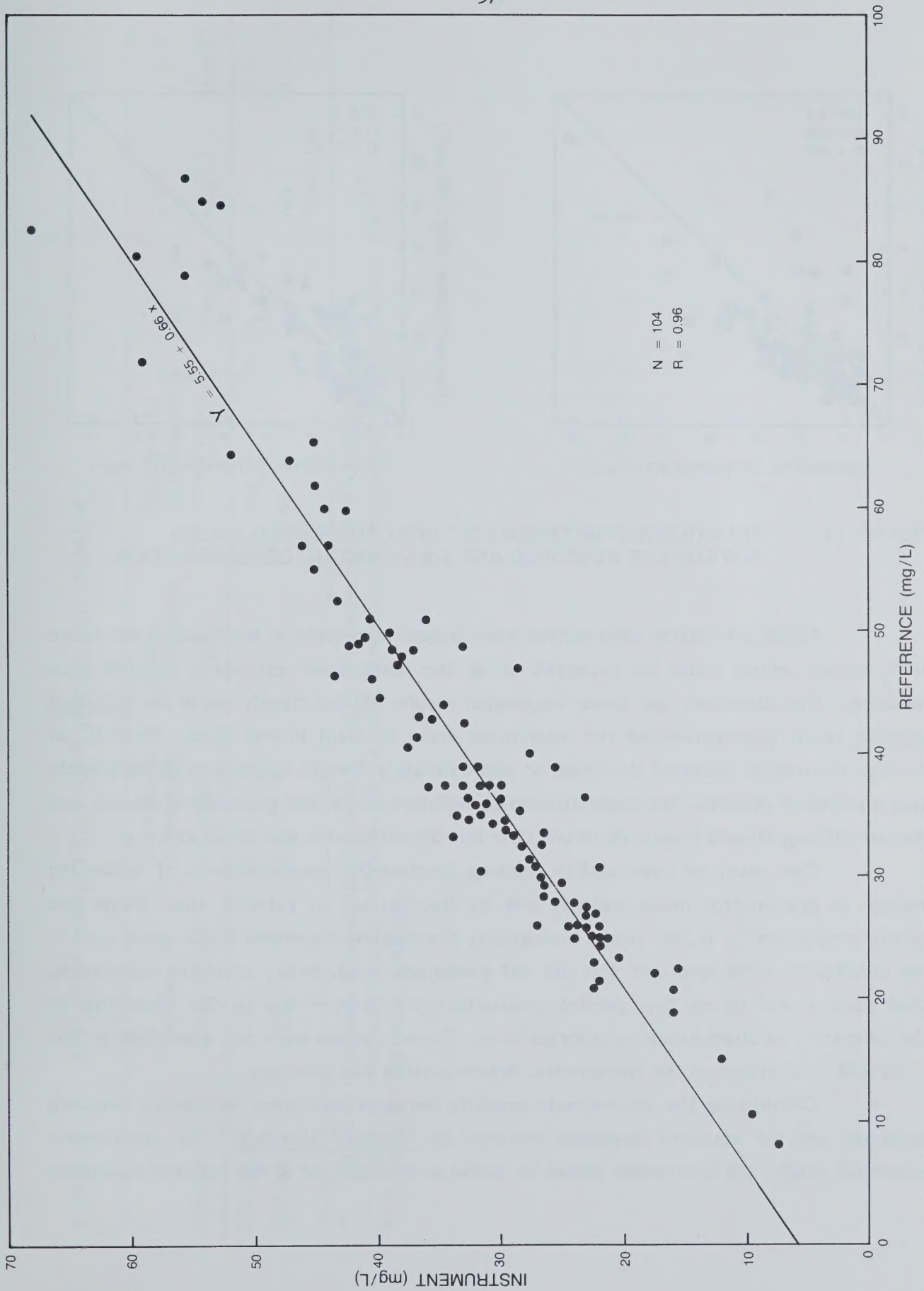


FIGURE 13 SCREENING EVALUATION OF EFFLUENT SUSPENDED SOLIDS SENSOR

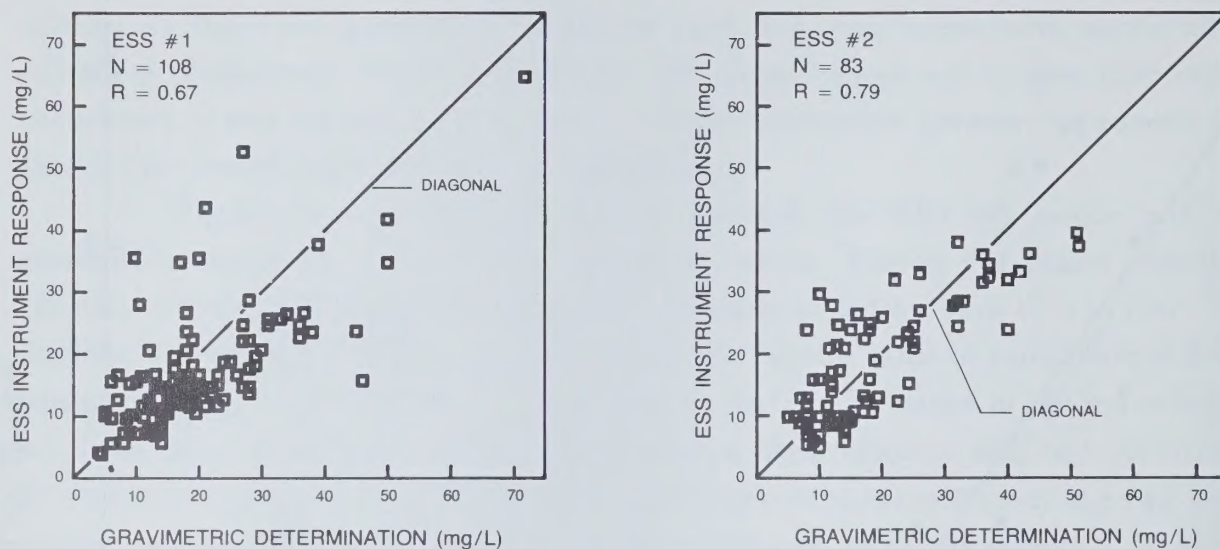


FIGURE 14 RELATIONSHIP BETWEEN EFFLUENT SUSPENDED SOLIDS INSTRUMENT RESPONSE AND GRAVIMETRIC DETERMINATION

These calculation alternatives were chosen to provide an estimate of the range of S_I values which could be expected using the alternative estimates of reference variance. The laboratory and linear regression results agreed closely while the Standard Methods result underestimated the instrument error at least in one case. Overall, an average instrument standard deviation of approximately 5 mg/L appears to be obtainable over a period of months. The mean difference between sensor and gravimetric results was statistically significant (Table 16) in one case but the difference was small at 2 mg/L.

Care must be exercised in relating photometric measurements of suspended matter to gravimetric measurements due to fluctuations in particle size, shape and optical properties¹². In this study, biologically flocculated suspended solids were used in the calibration technique, but this did not guarantee continuously accurate calibration. Over time, it was known that particle characteristics changed due to floc dispersion or the formation of filamentous microorganisms. These changes were not quantified in this study and their effect on the photometric determination was unknown.

Considering the approximate equality between estimated instrument standard deviation and the standard deviation reported by Standard Methods¹² for gravimetric suspended solids, the instrument should be useful as an indicator of the effluent suspended

TABLE 16 EFFLUENT SUSPENDED SOLIDS SENSOR PERFORMANCE

Sensor	Number of Data Points	Duration of Assessment (months)	Mean Difference (mg/L)	Significantly Different from zero, $P_{0.05}$	S_I^* (mg/L)	S_I^{**} (mg/L)	S_I^{***} (mg/L)
ESS no. 1	108	9	2	Yes	8	5	7
ESS no. 2	83	7	0	No	6	not measurable	6

* based on reference standard deviation of 2.1 mg/L determined from WTC laboratory tests.

** based on reference standard deviation of 5.2 mg/L determined from Standard Methods, Section 208D¹².

*** based on regression analysis.

fraction on a continuous basis. From the results, it is apparent that the photometric and gravimetric results are identical on the long-term average, but that instantaneous deviations between the two analysis techniques can exist. On the average the photometric instrument can yield valuable process information from the plant operating viewpoint and assist in calculating a continuous solids mass balance around the system.

The effluent suspended solids analyzers were relatively frequent maintenance items. The lack of a self-cleaning mechanism necessitated the frequent replacement or cleaning of flow-through photometer vials. Table 17 summarizes the frequency of vial replacement and calibration adjustments for the two sensors. During periods of high ambient relative humidity, condensation on the exterior vial surface also was a problem not easily prevented with this instrument.

3.4 Influent Suspended Solids

A self-cleaning Monitek 53-LE suspended solids analyzer was installed to monitor primary clarifier effluent suspended solids on the pilot plant. Figure 15 shows the relationship between the instrument and the gravimetric data during a two-week test period. The relationship is shown to be linear with a correlation coefficient of 0.84. A one-to-one correspondance between the instrument and gravimetric results was not expected since the instrument was operated without calibration after delivery from the supplier. An analysis of the differences between the observations and a fitted linear regression through the data yielded an instrument standard deviation of 20 mg/L suspended solids, compared to a reference standard deviation of 4.6 mg/L determined for primary effluent suspended solids gravimetric determinations at the WTC.

3.5 Feed and Recycle Flow Rates

Feed and recycle flow rates were monitored in the pilot plant using magnetic flow meters. These meters operate using the same principle as large scale units but bear little resemblance in scale. Each unit was periodically assessed by measuring the actual flow rate using a bucket and stopwatch. Results of the comparisons for four different flow meters are shown in Figure 16. Each instrument was highly correlated to the flow measured using the reference technique, with the lowest correlation coefficient having a value of 0.98. Table 18 lists the mean differences between instrument and reference, and the calculated standard deviations for the four magnetic flow meters in use. The value of the largest difference, 0.2 L/min, represents 2.9% of the average flow of 6.8 L/min

TABLE 17 MAINTENANCE AND CALIBRATION REQUIREMENTS FOR
LISLE-METRIX DRT-285 TURBIDIMETERS

Date	Requirement
7/1/80	Vials replaced and sensors recalibrated.
30/1/80	Sensor 1 calibration adjusted.
27/2/80	Sensors 1 and 2 recalibrated.
5/3/80	Sensor 1 vial replaced.
7/3/80	Sensor 2 vial replaced.
25/3/80	Sensor 1 and 2 vials replaced.
2/4/80	Sensor 1 and 2 vials cleaned.
28/4/80	Sensor 1 vial replaced
5/5/80	Sensor 2 vial replaced, sensor 1 vial cleaned.
15/5/80	Sensor 1 and 2 vials replaced.
22/5/80	Sensor 1 and 2 vials replaced.
2/6/80	Sensor 1 and 2 vials replaced.
18/6/80	Sensor 2 vial replaced.
15/7/80	Sensor 1 and 2 vials replaced.
28/7/80	Sensor 1 vial replaced.
11/8/80	Sensor 1 and 2 vials replaced.
25/8/80	Sensor 1 and 2 vials replaced.
1/9/80	Sensor 1 vial replaced.
2/9/80	Sensor 2 vial replaced.
15/9/80	Sensor 1 and 2 vials replaced.
22/9/80	Sensor 1 and 2 vials replaced.
20/10/80	Sensor 1 and 2 vials replaced.

throughout the monitoring period. All four flow meters had been constructed for maximum flows of 45 L/min and had been re-spanned for pilot plant usage in the range of 0-12 L/min.

The calculated standard deviations were based on the residuals remaining after fitting a straight line through the data, thus minimizing contribution to error due to inadequate calibration. The relative precision is approximately 3.7% at the average flow

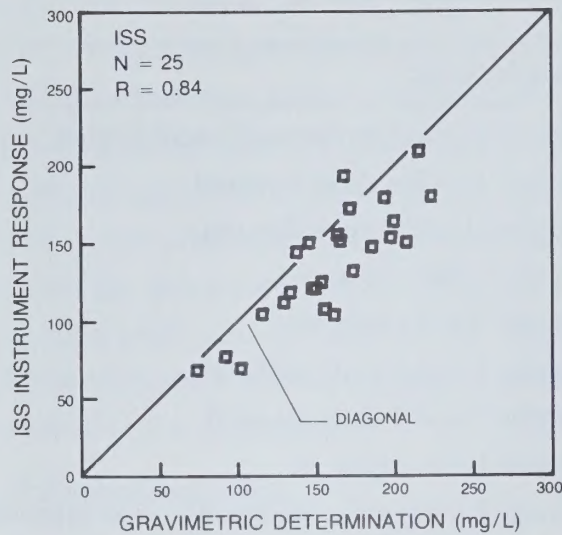


FIGURE 15 RELATIONSHIP BETWEEN INFLUENT SUSPENDED SOLIDS INSTRUMENT RESPONSE AND GRAVIMETRIC DETERMINATIONS

rate in the worst case and 2.5% based on the average of the S_I values. At higher absolute flow rates these values would be within the manufacturers' specifications.

As magnetic flow meters were available at the WTC, other types of flow sensors were not considered for the pilot plant. Other closed-pipe flow rate sensors could include pressure drop or ultrasonic sensors. Many types of open-channel flow meters are also marketed. Russell¹⁴ recently summarized some of the advantages and disadvantages of various types of flow meters, with calibration and maintenance requirements. Flow rate is perhaps the single most important variable in wastewater treatment facilities. Proper installation, maintenance, and calibration are essential to ensure that accurate flow data are obtained. Little can be gained from a pilot scale assessment of flow meters due to the deviations from full scale and the ambient environmental surroundings experienced in full-scale plants. One important consideration is the ability to check instrument calibration at full scale. The simple bucket and stopwatch technique is not usually possible and alternative procedures are necessary. Several possibilities exist, including:

- i) comparison to pump rating curves, which has the added benefit of checking pump wear simultaneously;

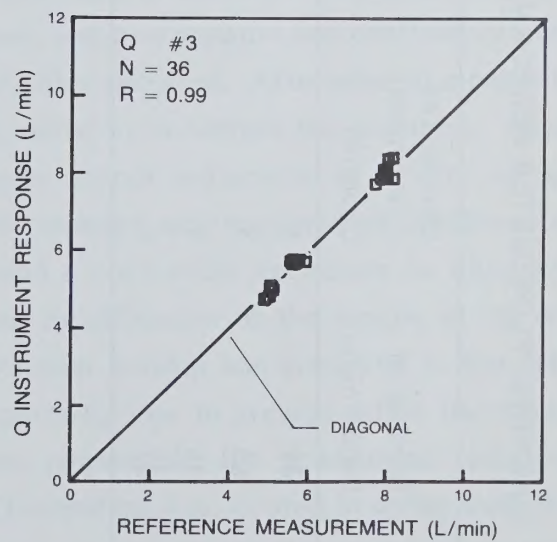
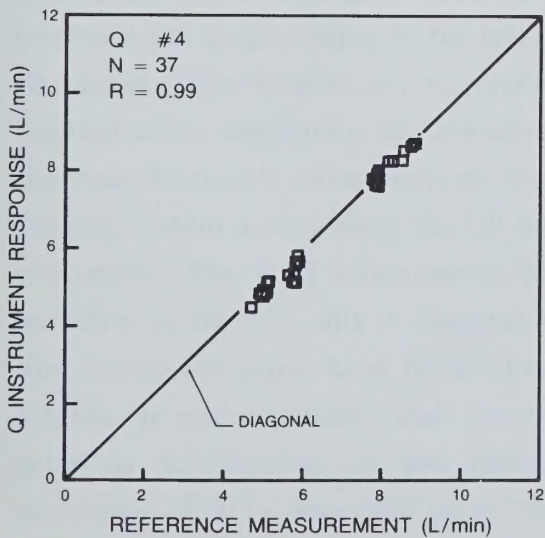
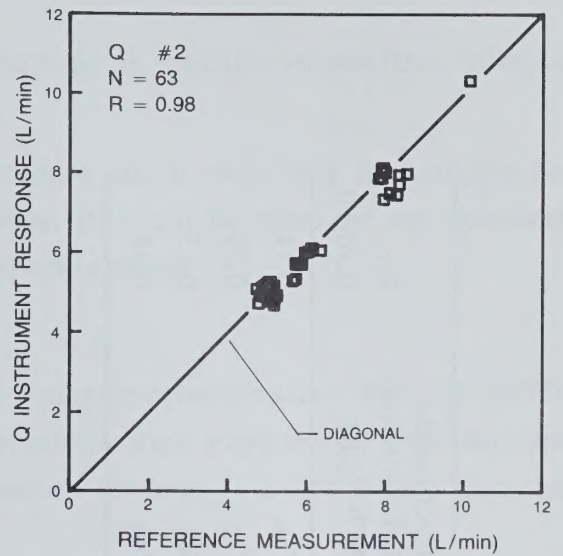
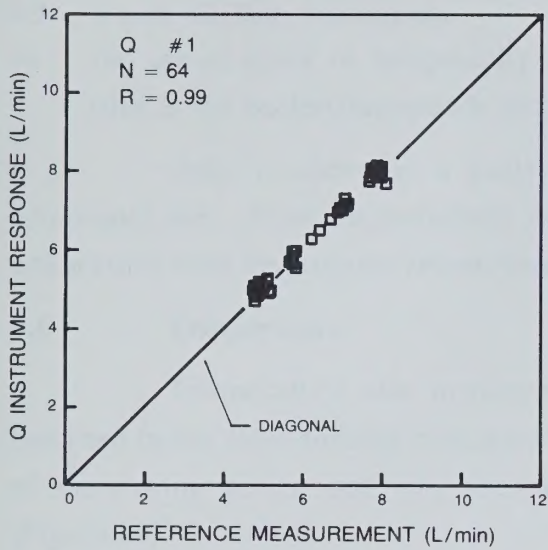


FIGURE 16 RELATIONSHIP BETWEEN MAGNETIC FLOWMETER RESPONSE AND VOLUME-TIME REFERENCE MEASUREMENT

TABLE 18 MAGNETIC FLOW METER PERFORMANCE

Sensor	Number of Data Points	Duration of Assessment (months)	Mean Differential (L/min)	Significantly Different from zero, $P_{0.05}$	S_I (L/min)
Q no. 1	64	5	0.05	Yes	0.14
Q no. 2	63	5	0.10	Yes	0.25
Q no. 3	36	4	0.01	No	0.13
Q no. 4	37	4	0.20	Yes	0.18

- ii) the diversion of flow through alternative meters;
- iii) the summation of flow streams through totalizing flow meters;
- iv) tracer dilution techniques;
- v) the use of spare or temporarily available tankage to measure volume/time changes (this is the bucket/stopwatch technique).

Only v) above is a fault-proof procedure but it may only be suitable for occasional use. Flow measurement instrumentation that can be removed for complete calibration must be strongly recommended for full-scale plants.

3.6 Temperature

Temperature was monitored using a resistance temperature detector (RTD) mounted in the flow-through configuration. No problems were experienced with this type of monitoring device and very accurate temperature readings ($\pm 0.02^\circ\text{C}$) were obtained (Figure 17).

3.7 Filterable Organic Carbon (FOC)

The low-temperature persulphate-ultraviolet oxidation principle developed by Goulden^{15,16} was chosen as the analytical method for FOC. For secondary effluent, recurring problems with instrument tube plugging due to buildup of biofilm and potassium persulphate crystals plagued operation. Other equipment problems included humidity and condensation in gas tubing to the infrared analyzer, and overpressure and overtemperature shutdowns. Two failures of lamp and power supply also occurred. After several months of unsatisfactory operation, the manufacturer was called in to address the problems. After the manufacturer's adjustment of the overpressure switch and advice to modify the air cooling system surrounding the UV lamp, further pressure and temperature problems did not occur. The WTC subsequently decided to add a cold-water condensor to eliminate humidity to the I.R. unit to improve calibration. Acidification of the sample at the on-line continuous paper tape filter eliminated microbial buildup and sloughing in the feed tubing. It was concluded that these buildups, partially due to growth within the tubing prior to acidification at the filter, had been responsible for downstream plugging problems. A 52- μ pore size paper tape filter (Technicon) was located in series with the Foxfilter to improve suspended solids removal. After these efforts, the analyzer operated satisfactorily on secondary effluent with approximately 0.5 to 1.0 person-day per week necessary for routine calibration and maintenance, including tube changes, chemical

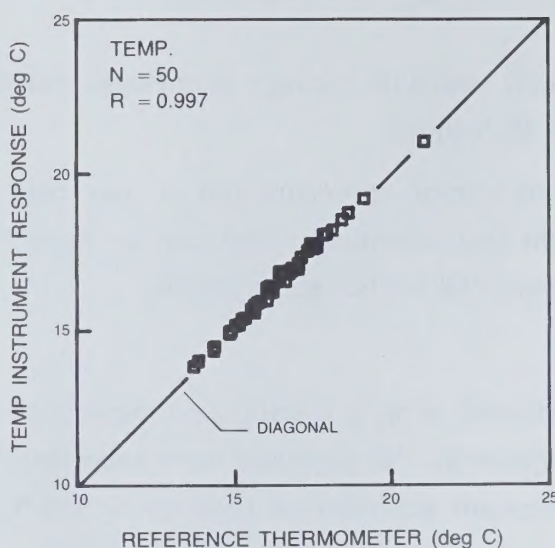


FIGURE 17 RELATIONSHIP BETWEEN RTD
AND REFERENCE THERMOMETER

make-up and O₂ cylinder change. For this instrument, sample pretreatment is essential before successful operation can be expected.

Figure 18 summarizes the results from the on-line FOC analyzer during five days operation in a one-month period. Based on the paired data, the mean difference between the on-line instrument and the reference analysis (Beckman Model 915 analyzer) was 1 mg/L with an instrument standard deviation of 1.2 mg/L. With proper sample conditioning and attentive operator maintenance, this analytical method can give reliable operating information. Indications are that the instrument can be used to monitor primary effluent (influent) FOC; however, this has not been attempted to date with the sample conditioning modifications mentioned above.

A limited amount of data for influent FOC prior to the instrument modifications is shown in Figure 19. It was apparent that the instrument response was generally less than the reference Beckman instrument, although a linear relationship was indicated. Maintenance problems (plugging, electrical, calibration) prevented the collection of further data before the instrument was shifted to the plant effluent streams and efforts made to perform the indicated alterations.

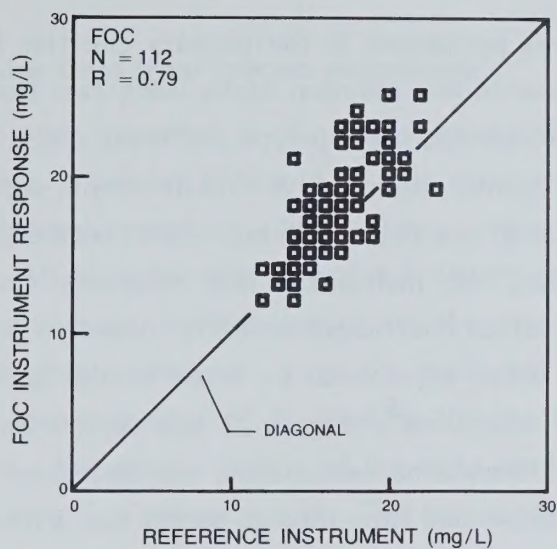


FIGURE 18 RELATIONSHIP BETWEEN EFFLUENT FOC INSTRUMENT RESPONSE AND REFERENCE FOC

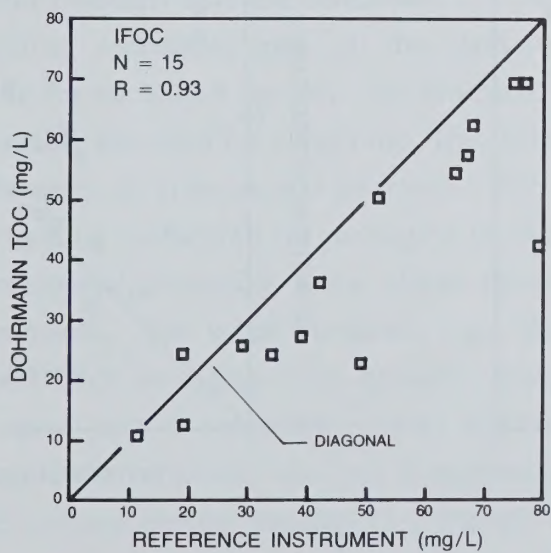


FIGURE 19 RELATIONSHIP BETWEEN INFLUENT FOC INSTRUMENT RESPONSE AND REFERENCE FOC

3.8 pH Measurement

Measurement of pH was performed in the primary clarifier feed using a non self-cleaning dip-type electrode and in the aeration tanks using two flow-through cells. Figure 20 depicts the relationship between the dip-type electrode and a reference Orion Model 404 analyzer during a five-month period. Five measurements significantly higher than the diagonal (Figure 20) occurred sequentially in one month before corrective action was taken. Excluding these data, the instrument and reference unit had a mean difference of 0.06 units and correlation coefficient of 0.97. Based on paired data the S_I value was calculated to be 0.08 units, approximately equal to the accepted value for electrodes operated under normal conditions⁵. Figure 20 also depicts data for one flow-through pH sensor. The mean difference between sensor and reference was 0.02 units with an S_I value of 0.05 units. The second flow-through sensor had a mean difference of 0.10 units with S_I value 0.09 units.

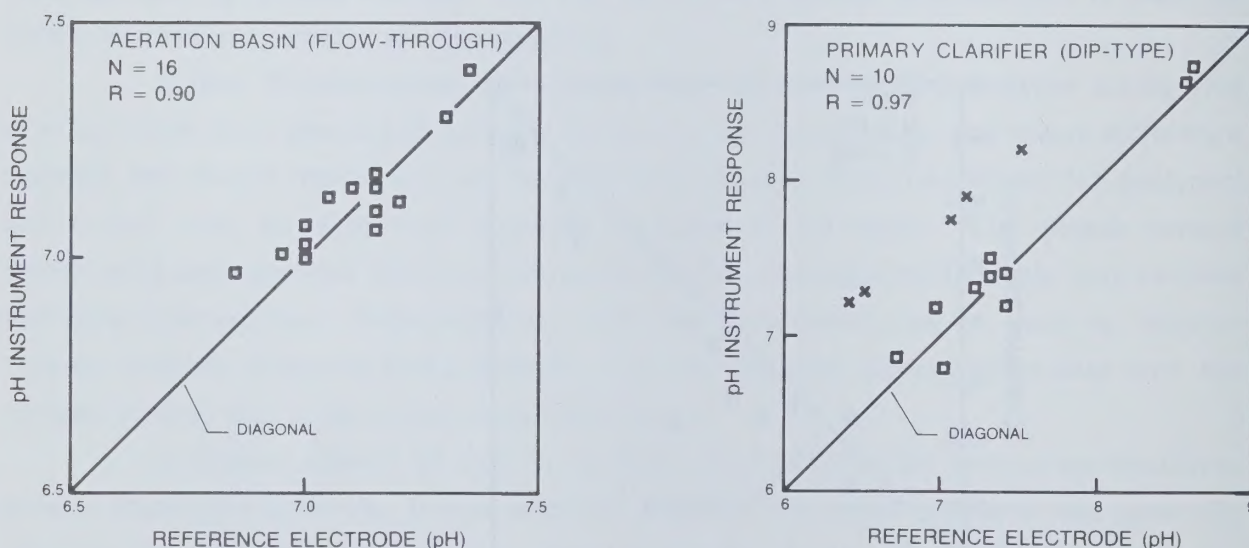


FIGURE 20 RELATIONSHIP BETWEEN pH INSTRUMENT RESPONSE AND REFERENCE ELECTRODE

4 SAMPLES OF DATA COMPILED FOR PLANT MONITORING

4.1 On-Line Data from Process Instruments

Data were reported to the plant operating staff in three formats: a 24-h graphical summary, a tabular listing of 15-minute averages used for graphical summary, and a daily summary report of the on-line process variables together with off-line laboratory data. All three formats provided different perspectives of the data generated. The graphical summary of the data was by far the most informative and easy to interpret or question at a glance; however, with the computer plotter used, approximately one person-hour per day was required to produce the graphs. However, this work could be easily automated. The tabular listing of the data used to generate the graphs could be obtained in less than five minutes daily. This approach provided a very rapid summary of all of the instrument data which could be scanned for inconsistencies or to monitor trends and events. In general, however, the graphical summaries were more easily inspected. The daily summary report was not as useful as the other two forms of data presentation and was relatively time-consuming from a personnel and computer time viewpoint. It therefore fell into disuse and was discontinued. A further problem with this report was that off-line laboratory data consistently took several days to compile and was time-consuming to enter manually into the computer.

Graphical representations of the data were produced for each primary measured variable for each 24-h period. For practical purposes, a 15-minute average of each primary variable was used for reporting. This 15-minute average was based upon 180 discrete measurements at five-second intervals. For some variables, e.g., flow, DO, a shorter period could be considered for averaging to catch any dynamic changes; however, this was not considered necessary since alarm conditions could be flagged from the discrete measurements. For other variables, e.g., MLSS, temperature, longer intervals could be considered for averaging since dynamic changes are considerably slower. The relatively low capital cost of computer memory and storage means that large amounts of data can be compiled at relatively low cost if necessary. Using the HP 1000 system with 120 M-byte disc storage device resulted in a capital cost of approximately 4¢/100 real numbers, for example. Thus the cost of storing 15-minute averages for each primary measurement was only about 4¢ per day.

To illustrate the effectiveness of graphical presentation of the on-line data, examples are presented for each of the primary variables.

4.2 Dissolved Oxygen and Air Flow Rate

The most dynamic indicator of the response of the activated sludge process to changes in gross process loading or process inhibition is the DO concentration. It is also a significant variable from an energy standpoint since in activated sludge systems aeration dominates energy expenditures. Under DO controlled conditions, air flow rate becomes the dynamic indicator of load or process conditions. Either DO or air flow rate are strongly related to biological activity.

Figure 21 illustrates these concepts for a case of the two parallel completely-mixed pilot plants receiving the identical feed loading. In one case the air flow rate was manipulated automatically to achieve a constant set point DO concentration. In the other case the air flow rate was controlled to a constant set point resulting in a variable reactor DO concentration. It is clear from Figure 21 that the variation in air flow rate for the constant set point DO concentration case reflected the variation in the DO concentration for the constant air flow rate case. These data also show the degree of variation in DO concentration which can be experienced in an activated sludge reactor subjected to diurnal variations in hydraulic and organic loading where the air flow rate in the manually controlled case is sufficient to prevent anaerobic or anoxic conditions at the peak loading. The degree of variation is governed by several factors¹⁷:

- hydraulic disturbances of influent wastewater or of return activated sludge,
- changes in feed pattern,
- organic disturbances,
- nitrification,
- denitrification,
- toxic disturbances,
- recycle from other process streams, e.g., digester,
- disturbances in air or oxygen supply or in air transfer efficiency,
- changes in excess sludge wasting patterns or in solids retention time (SRT).

Many of the above disturbances are not easy to measure directly. Measurement of DO and its variation, or conversely of air flow rate in the DO controlled case, could permit inferences to be made about some of these disturbances by use of on-line

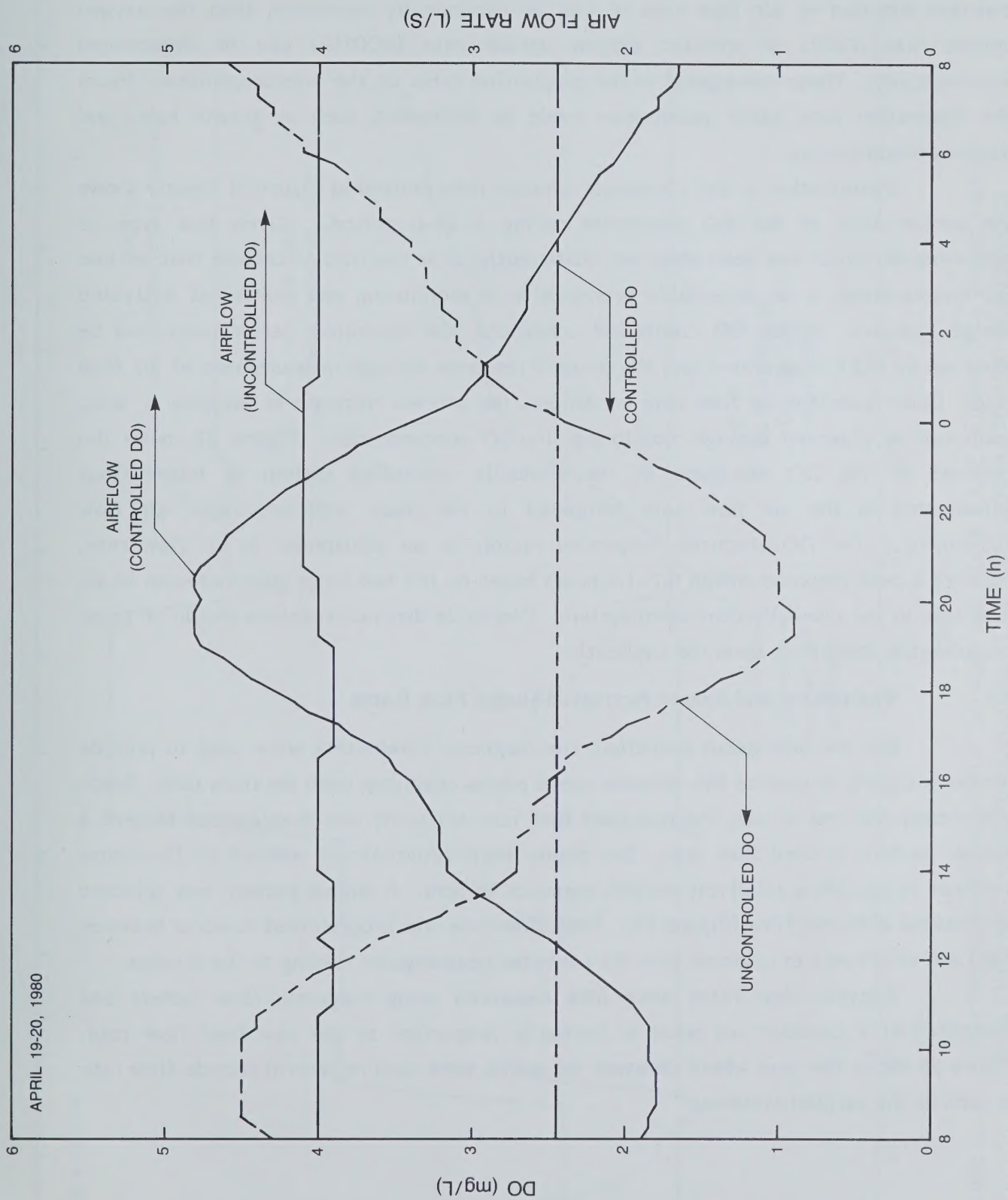


FIGURE 21 ON-LINE MEASUREMENTS OF DO AND AIR FLOW RATE FROM PARALLEL PILOT PLANT SYSTEMS DURING 24-h PERIOD

computing power¹⁷. For example if the O_2 transfer coefficient can be considered to be a constant function of air flow rate or can be dynamically measured, then the oxygen uptake rate (OUR) or specific oxygen uptake rate (SCOUR) can be determined automatically. These correspond to the respiration rates of the microorganisms. From the respiration rate, other parameters could be estimated, such as growth rates and nutrient requirements.

Examination of the 15-minute average data plotted in Figure 21 clearly shows the performance of the DO electrodes during a 24-h period. Given this type of performance, which has been observed consistently, it is realistic to assume that on-line DO measurement is an acceptable prerequisite in monitoring and control of activated sludge systems. Under DO controlled conditions, the controller performance can be observed by DO measurement and the process response through measurement of air flow rate. Under constant air flow rate conditions, the process response to variable or toxic loads can be observed through monitoring the DO concentration. Figure 22 shows the response of the DO electrode in the manually controlled system to intermittent adjustments in the air flow rate compared to the plant with automatic air flow adjustment. The DO electrode responded rapidly to an adjustment in air flow rate, reaching a peak response within 0.7-1.0 hours based on the two large step increases in air flow rate in the manually controlled system. Electrode dynamic response should be given consideration depending upon the application.

4.3 Wastewater and Return Activated Sludge Flow Rates

For the pilot plant operation, the magnetic flowmeters were used to provide feedback signals to control the variable speed pumps supplying each aeration tank. Since a minicomputer was in use, the raw feed flow rate set point was programmed to give a diurnal pattern in feed flow rate. Set points were automatically altered at 10-minute intervals to provide a relatively smooth variation in flow. A simple pattern was selected to simulate a diurnal flow (Figure 23). Peak flow rate was programmed to occur between 2000 and 2015 hours to coincide with the expected peak organic loading to the process.

Recycle flow rates were also measured using magnetic flow meters and controlled at a constant set point or varied in proportion to the raw feed flow rate. Figure 23 shows the case where constant set points were used to control recycle flow rate in each of the parallel systems.

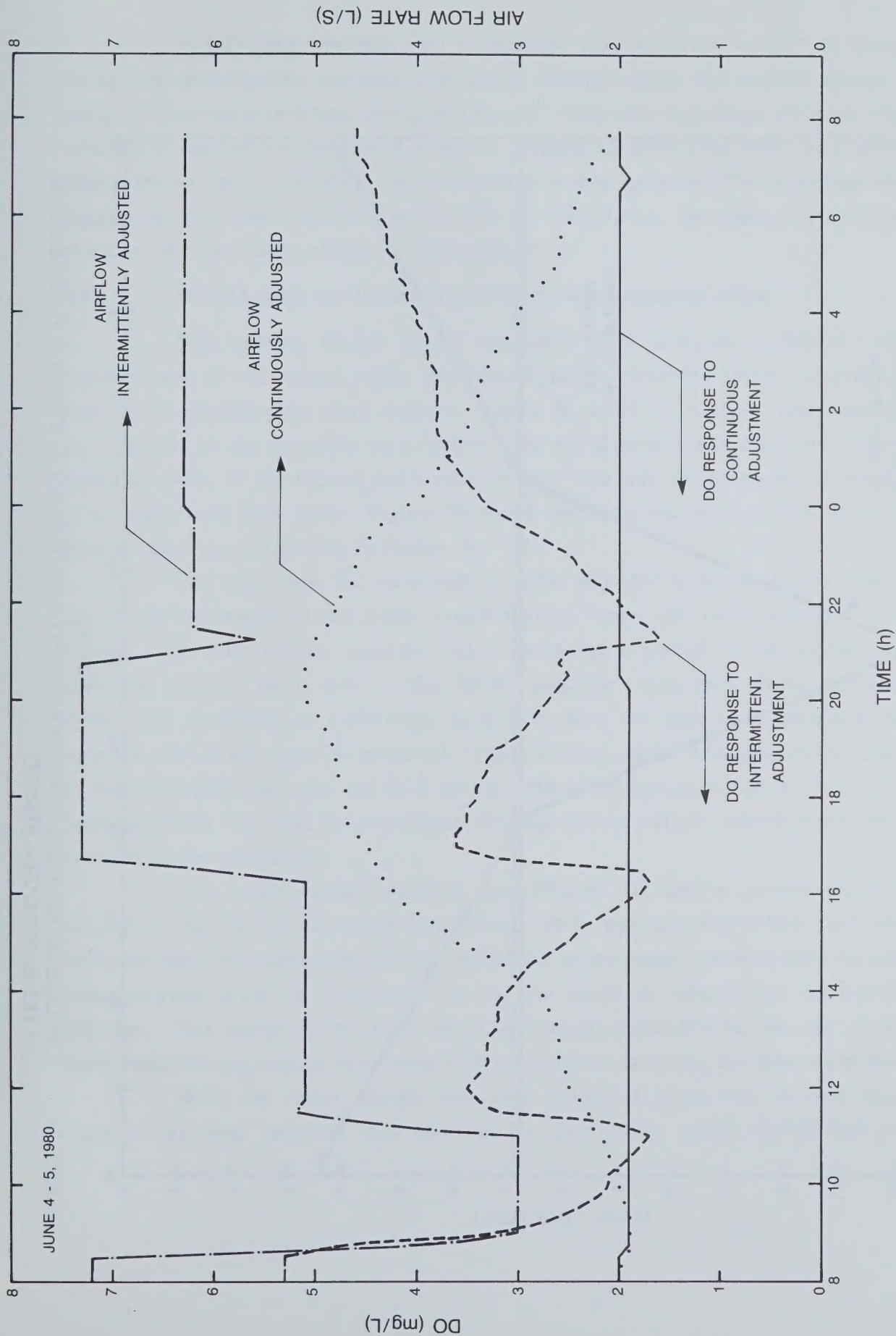


FIGURE 22 ON-LINE MEASUREMENTS OF DO AND AIR FLOW RATE DURING 24-h PERIOD WITH INTERMITTENT MANUAL ADJUSTMENT OF AIR FLOW RATE AND CONTINUOUS AUTOMATIC ADJUSTMENT

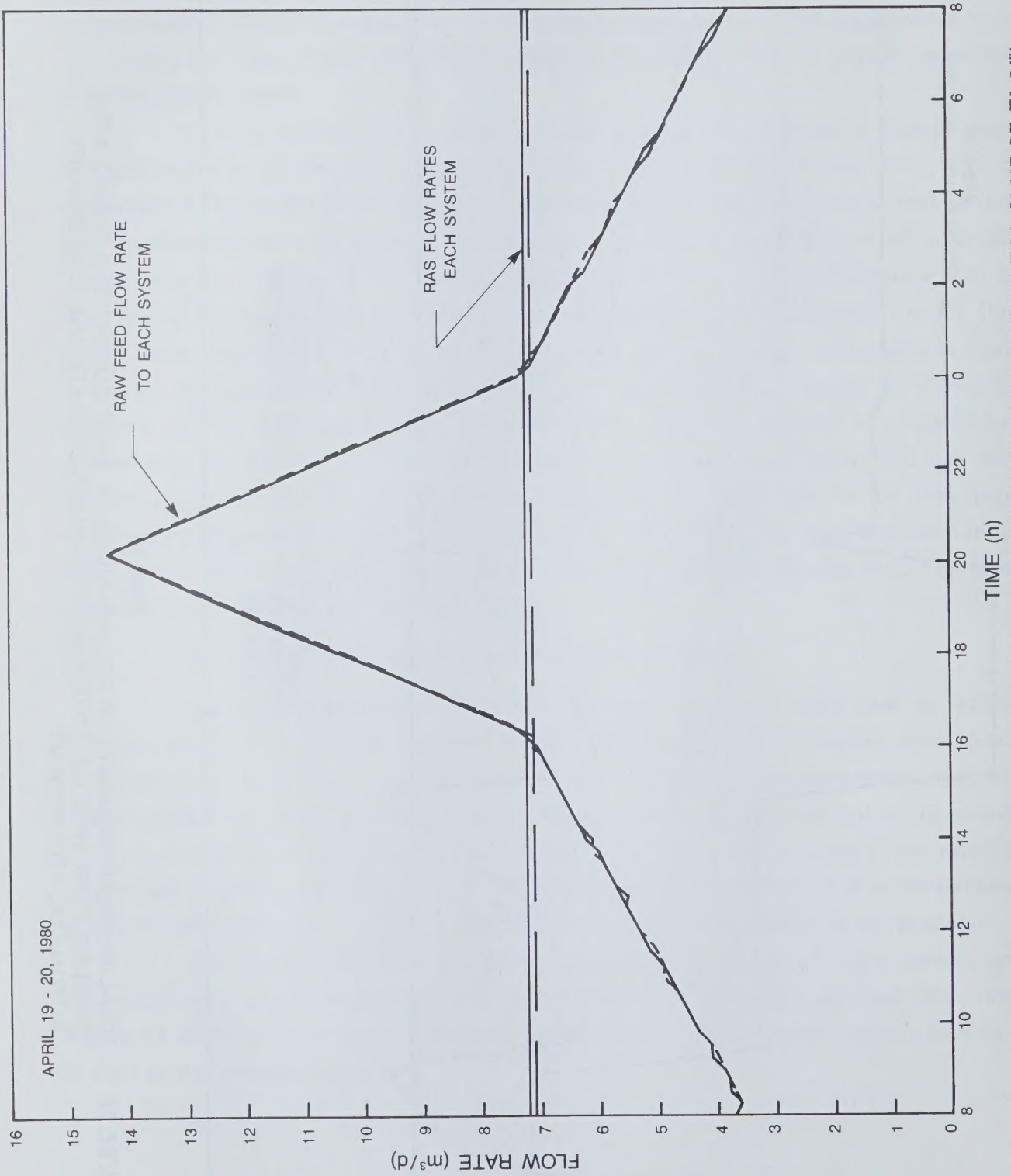


FIGURE 23 ON-LINE MEASUREMENTS OF RAW FEED AND RETURN ACTIVATED SLUDGE FLOW RATES DURING 24-h PERIOD

In full-scale systems, raw wastewater flow rates are subject to many well-recognized disturbances including predictable diurnal cycles and random shocks due to pump station characteristics, precipitation, etc. Flow rate is perhaps the most important variable in wastewater treatment systems. Analog systems have been used to measure flow rates for years, providing chart recordings to the operator. The advantage of digital logging of flow rate data will be its use for calculating secondary variables such as clarifier overflow rates, oxygen uptake rates, etc.

4.4 Mixed Liquor and Return Activated Sludge Suspended Solids

The Monitek CLAM 52-LE suspended solids analyzers provided continuous measurement of the mixed liquor and return sludge suspended solids concentrations in both of the parallel pilot plant systems. Figure 24 shows the analyzer responses during a 24-h period. In one plant the recycle flow rate was automatically controlled to equal the feed flow rate. In the second plant, recycle flow rate was set constant and equal to the 24-h mean feed flow rate. Figure 25 shows the feed and recycle flow rates for the parallel plants corresponding to Figure 24.

The data show the variations in solids detected by the analyzers based on the 15-minute averages. Mixed liquor concentrations were relatively constant during the period. The only readily apparent MLSS variation occurred in the system with the constant recycle feed rate. The MLSS analyzer registered from approximately 2 500 mg/L at 0800 h to 2 200 mg/L at 2100 h when the peak mass transport from the aeration tank to the clarifier occurred. This corresponded to an approximate 12% change in reactor solids mass over the 24-h period. The MLSS concentration in the reactor with variable return flow rate did not suggest any significant shift in reactor solids concentration during the period.

The return sludge analyzer data (Figure 24) clearly showed the variations evident in the return solids concentrations. With the constant return rate case, the analyzer detected significant diurnal variations in the solids concentration varying from approximately 4 600 to 7 200 mg/L during the cycle as compaction occurred in the clarifier. This degree of variation would be virtually impossible to measure continuously using conventional manual techniques without intensive sampling and analysis efforts.

With the return sludge flow rate varied in proportion to feed flow rate, significantly less variation was observed in the return sludge solids concentration

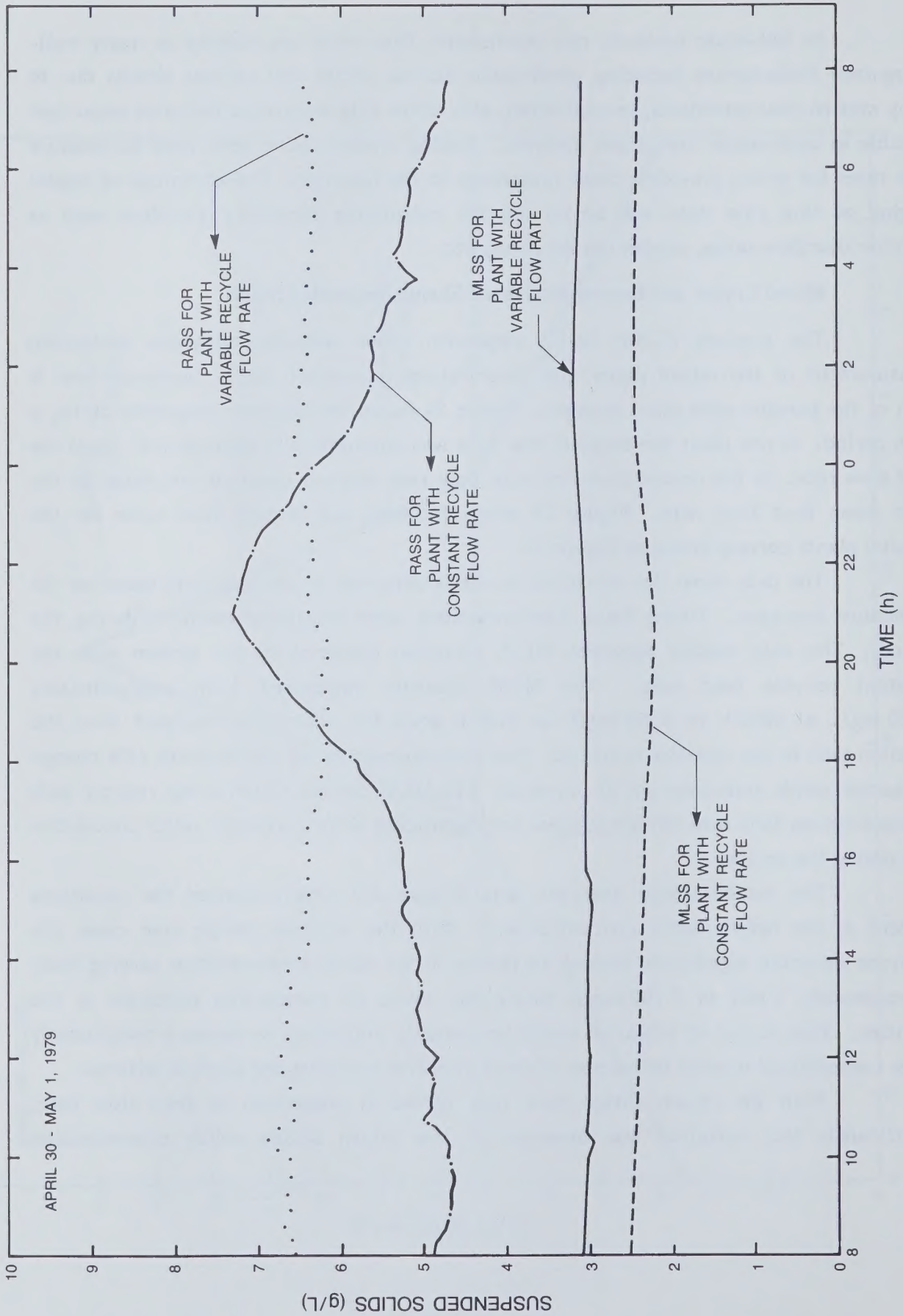


FIGURE 24 ON-LINE MIXED LIQUOR AND RETURN ACTIVATED SLUDGE SUSPENDED SOLIDS MEASUREMENTS DURING 24-h PERIOD WITH AND WITHOUT CONSTANT RECYCLE RATE

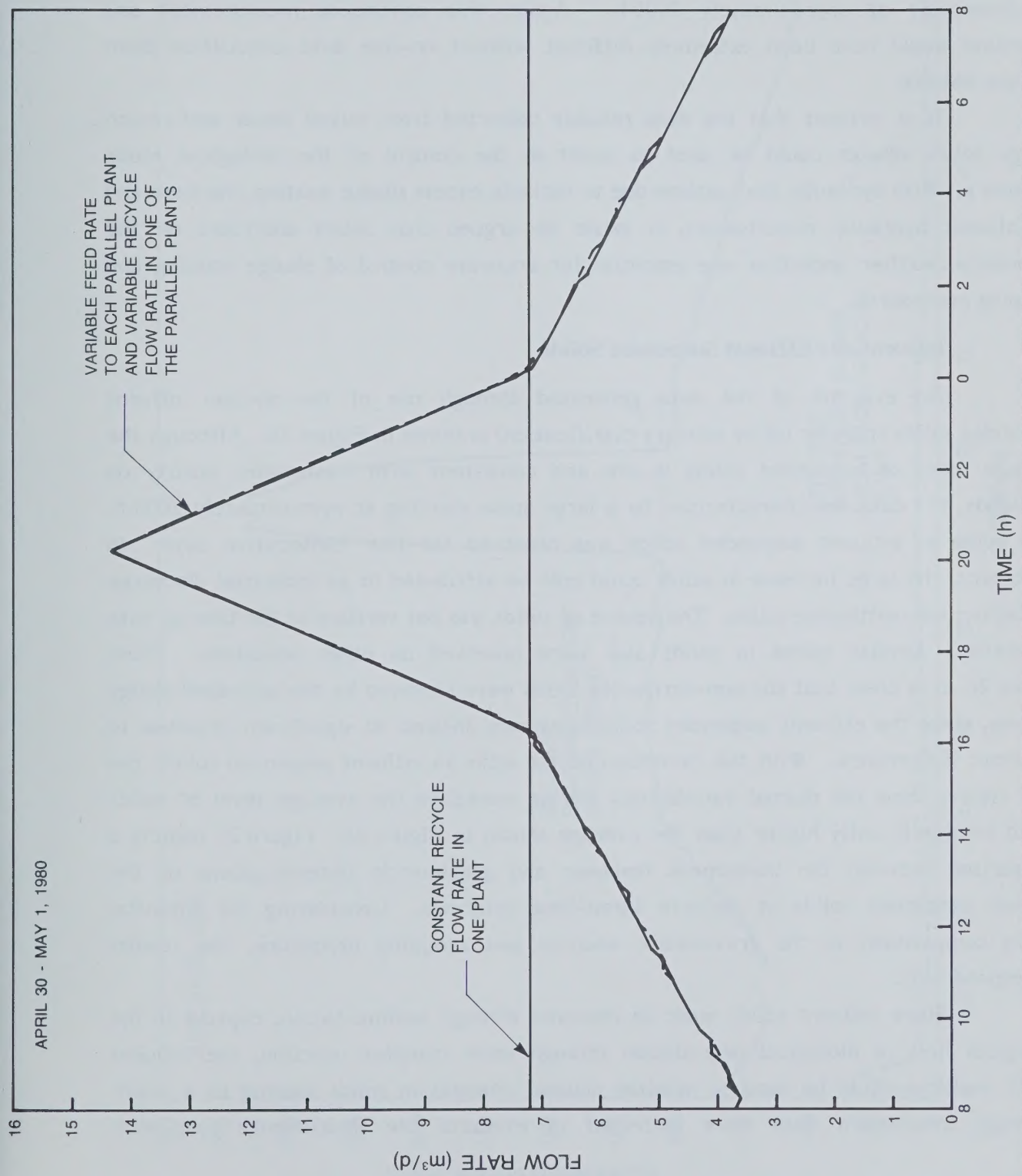


FIGURE 25 ON-LINE FEED AND RECYCLE FLOW RATES CORRESPONDING TO ON-LINE SOLIDS MEASUREMENTS

(Figure 24). Evidence of a small decrease in return sludge solids concentration could be observed at the peak hydraulic and peak return sludge flow rates, occurring simultaneously at approximately 2000 h. Again, this continuous measurement and detection would have been extremely difficult without on-line data acquisition from process sensors.

It is evident that the data reliably collected from mixed liquor and return sludge solids sensors could be used to assist in the control of the biological solids inventory. With hydraulic fluctuations due to variable excess sludge wasting practices and to influent hydraulic disturbances, it could be argued that solids analyzers on the secondary clarifier underflow are essential for accurate control of sludge wasting and pumping procedures.

4.5 Influent and Effluent Suspended Solids

An example of the data generated through use of the on-line influent suspended solids analyzer (after primary clarification) is shown in Figure 26. Although the average level of suspended solids is low and consistent with wastewater quality on weekends, the data are characterized by a large spike starting at approximately 2000 h. This spike in influent suspended solids was observed for four consecutive days. In retrospect, the large increase in solids could only be attributed to an industrial discharge containing non-settleable solids. The source of solids was not verified at the time of data collection. Similar spikes in solids also were observed on other occasions. From Figure 26, it is clear that the non-settleable solids were removed by the activated sludge process, since the effluent suspended solids analyzers showed no significant response to the input disturbance. With the exception of the spike in influent suspended solids, the data clearly show the diurnal variability. During weekdays the average level of solids would be significantly higher than the average shown in Figure 26. Figure 27 depicts a comparison between the instrument response and gravimetric determinations of the influent suspended solids at discrete three-hour intervals. Considering the potential errors compounded in the gravimetric analysis and sampling procedure, the results correspond well.

Since influent solids must be removed through sedimentation, capture in the biological floc, or biological degradation through some complex reaction, the influent solids analyzer could be used to monitor unusual changes in solids loading to a plant. Although insufficient data were collected to evaluate the instrument's long-term

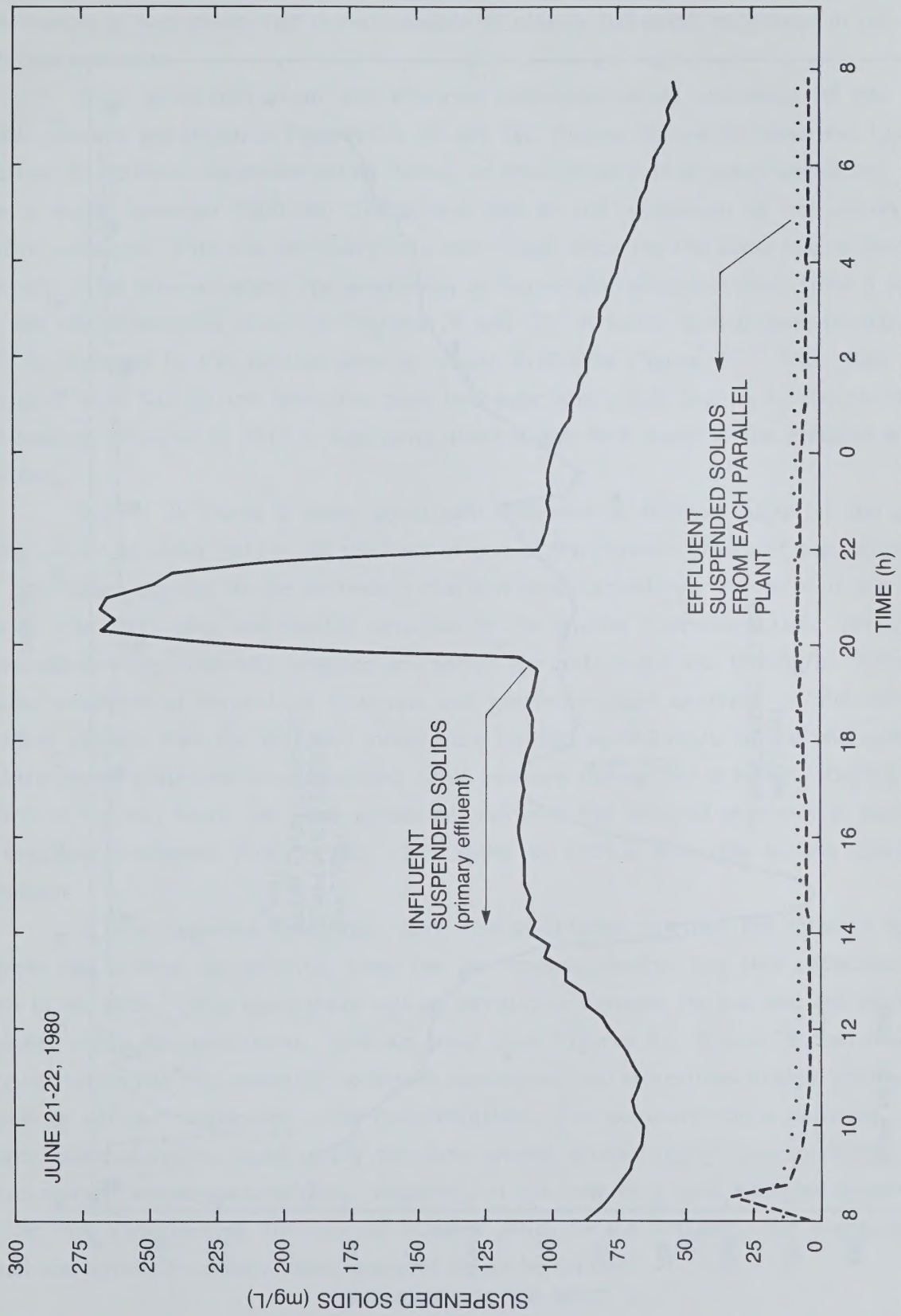


FIGURE 26 ON-LINE INFLUENT AND EFFLUENT SUSPENDED SOLIDS CONCENTRATIONS DURING 24-h PERIOD

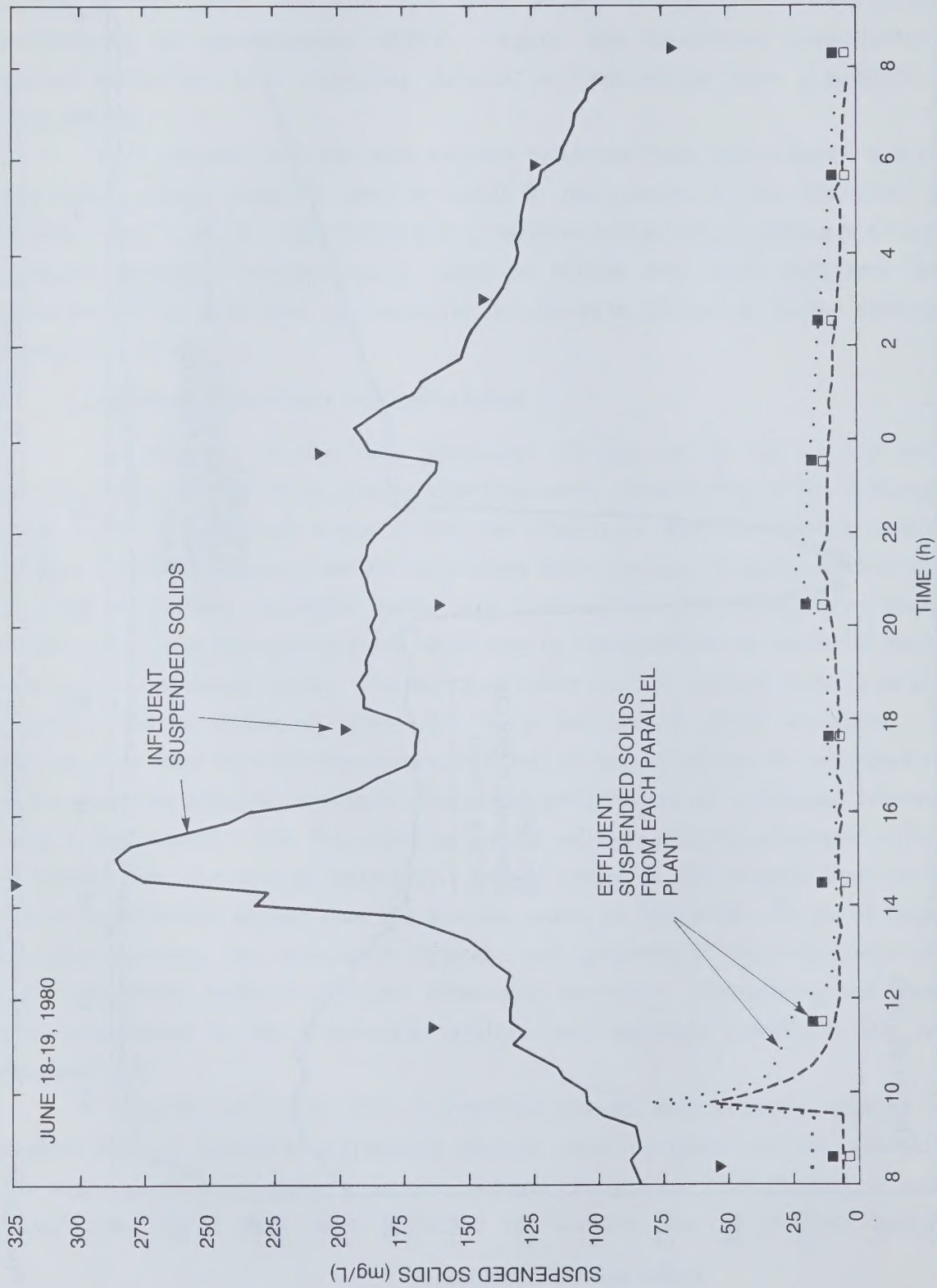


FIGURE 27 COMPARISON OF INSTRUMENT RESPONSE AND GRAVIMETRIC DETERMINATIONS FOR INFLUENT AND EFFLUENT SUSPENDED SOLIDS - JUNE 18-19, 1980

performance, it was clear that it was capable of closely following variations in influent solids concentration.

Data generated from the effluent suspended solids analyzers of the two parallel streams are shown in Figures 26, 27 and 28. Figures 26 and 27 show the typical variations in effluent suspended solids during acceptable periods of plant operation. The spike in solids between 0800 and 0930 h was due to the washdown of the secondary clarifier surfaces. This was necessary on a daily basis since the clarifiers had no surface skimmers. The time at which the washdown occurred was always evident from a spike with the characteristics shown in Figures 26 and 27. A small diurnal peak in effluent solids is depicted in the on-line data at about 2130 h in Figure 27. This peak was coincident with but shifted from the peak hydraulic and solids loading to the clarifier. Peak loading occurred at 2015 h, signifying about a one hour delay in the effluent solids response.

Figure 28 shows a more significant response in effluent solids at the peak loading period at about 2015 h. In the case of one of the parallel plants, it was observed that the sludge blanket in the secondary clarifier was carried over the weir at the high loading. The carry-over was readily detected by the on-line instrumentation. However, the maximum range manually selected and set on the instrument was 100 mg/L. Discrete samples collected at three-hour intervals and gravimetrically analyzed on this day of operation showed that the effluent solids were as high as 642 mg/L in the one system. The instrument registered the maximum value possible during this interval. During the balance of the day there was good agreement between the discrete gravimetric samples and analyzer responses (Figure 28). The spike at 0900 h was due to the clarifier washdown.

It was apparent from this day's results (Figure 28) that the influent solids analyzer had drifted significantly from the gravimetric results, but still reflected the trends in the data. Once again there was no correlation between the influent and effluent suspended solids concentrations. It is apparent from Figures 26, 27 and 28 that on-line instrumentation has the capability to detect continuous, and sometimes sudden, changes in influent or effluent suspended solids concentration. For accurate solids balances, only on-line instrumentation could supply the data needed without using time-consuming and tedious manual sampling techniques. However, in the case of a well-operated secondary clarifier not experiencing the loss of blanket solids in the effluent, the precision of manual and automatic sensor-based analyses would be similar.

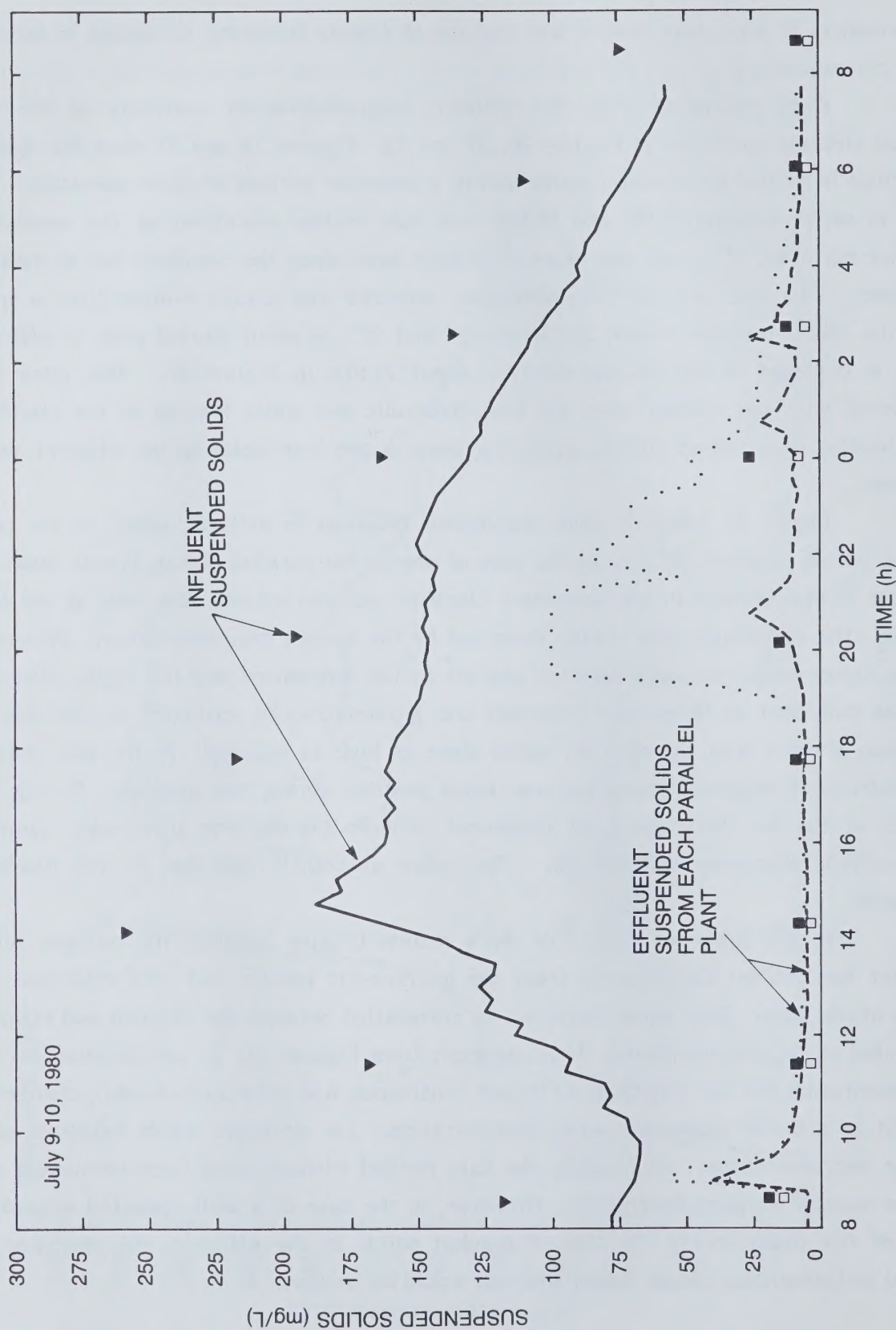


FIGURE 28 COMPARISON OF INSTRUMENT RESPONSE AND GRAVIMETRIC DETERMINATIONS FOR INFLUENT AND EFFLUENT SUSPENDED SOLIDS - JULY 9-10, 1980

4.6 pH Measurement

In many wastewater treatment processes, pH is an important variable. Often acidity or alkalinity are the variables of interest, but pH itself is important in living systems. Figure 29 shows a typical example of the responses of the pH electrodes in the feed (before primary clarification) and in the aeration tanks of the two systems. The feed pH varied in an uncontrolled fashion due in all likelihood to the discharge of industrial contaminants to the sewer system. It is apparent that both acidic and basic materials have been discharged since pH varied from as low as 6.5 to peaks as high as 10.3 units. The rate of change of influent pH is pronounced, lending itself to the early detection of significant pH perturbations.

The pH's measured in the aeration tanks are significantly affected by the incoming pH, but are delayed about one hour and damped hydraulically and biochemically. This is an example of a case where feed forward control based on influent pH and acid/base information could be applied for better pH control in the aeration system. This was not attempted in this study. Again, the rate of change of pH as given by the 15-minute averages plotted in Figure 29 could be used as a good indicator of upsets to the system. Both pilot plant systems reacted in the same way to the pH disturbance but with an offset of about 0.2 pH units which is within the limits that can be expected based on the sensor evaluation. Changes in pH observed on this day did not affect the activated sludge process as measured by the specific oxygen utilization rate. It is apparent that, where pH is a significant concern from a process viewpoint, the on-line continuous sensor-based data would be timely and informative.

4.7 Filtered Organic Carbon

As indicated in the instrument evaluation section, several problems had to be overcome with the on-line FOC analyzer before it could be used effectively. After the appropriate modifications had been made, the analyzer was used to continuously monitor the effluent organic carbon concentration from the two pilot plant systems. Even after the modifications were made, occasional problems occurred. These were usually associated with the continuous filter, which could tear or jam. If the tape failed to advance, the filtration rate decreased to essentially zero resulting in a loss of signal. However, the analyzer performed relatively well after the modifications.

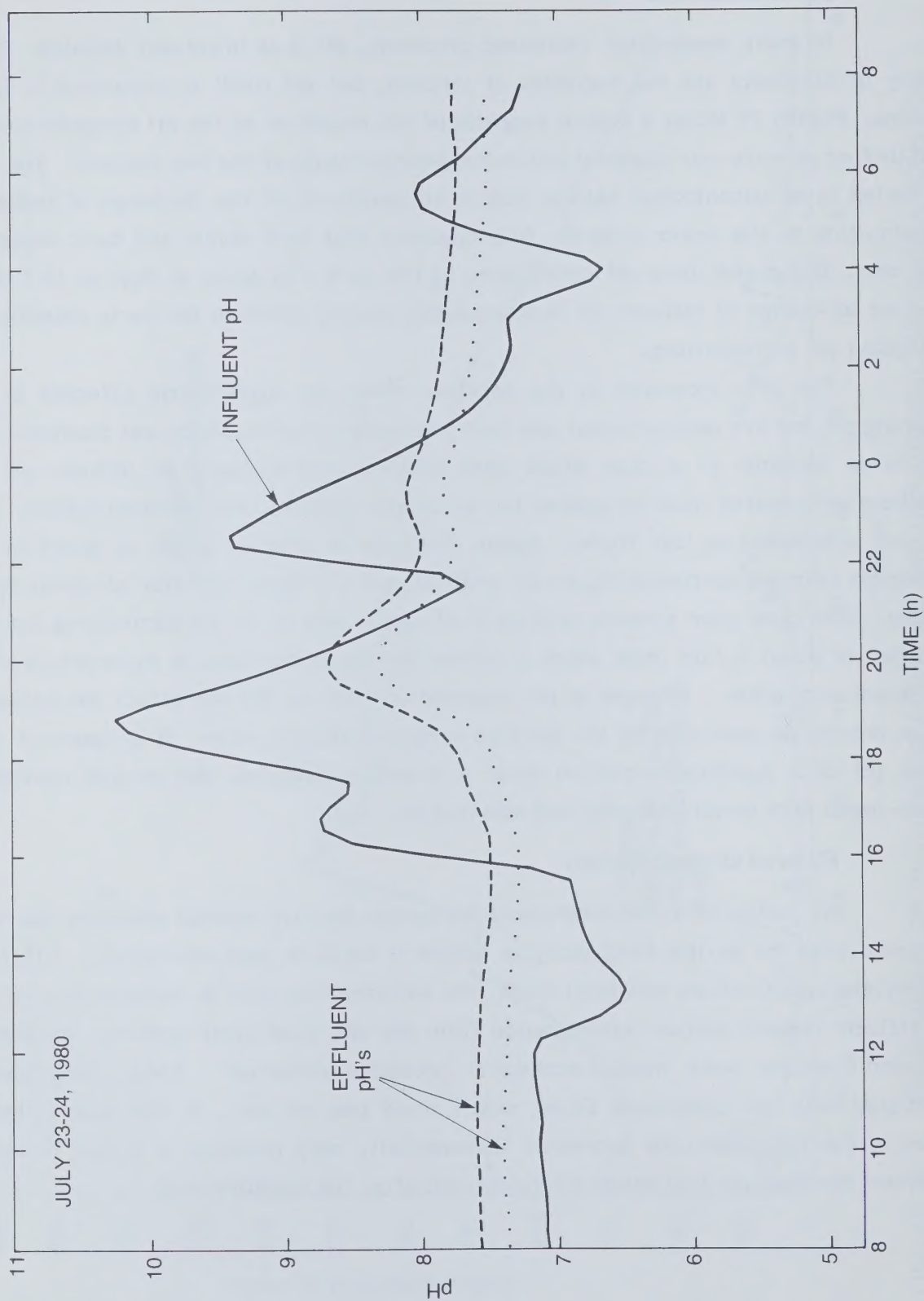


FIGURE 29 INFLUENT AND EFFLUENT pH DURING 24-h PERIOD

Figure 30 shows results at one-hour intervals for each of the pilot plant systems. The analyzer was controlled to alternate between each system with a period of one hour. The data shown are for a period during which a dynamic step-feed program controlled the flow distribution in one of the systems. This lead to a higher concentration in the step feed system during the part of the day having peak organic loading compared to the parallel completely mixed system. Data collected in the routine fashion of automatically sampling the effluent and analyzing the filtrate using the reference technique are also plotted for comparison. During most of the day, the on-line and reference data deviate from one another within an acceptable range based on the initial evaluation program. No explanation can be made for the larger deviations between 1200 h and 1600 h. On the average, the instrument yielded a lower response than the reference technique for both systems. This could have been due to differences in calibration, sampling technique and sample handling, or to the differences in sample filtration.

4.8 Temperature

Temperature of the raw feed to the primary clarifier was controlled thermostatically to eliminate seasonal variations, while temperature was measured continuously in the aeration tank of one of the systems (Figure 31). Since temperature was controlled, only heat transfer effects were of interest in the temperature data. These effects were shown as a diurnal oscillation in temperature with the flow rate of feed to the systems. At the lower flow rates in the early morning hours, the increased hold-up time allowed the temperature in the aeration tank to be driven towards the ambient temperature. As flow rate increased during the day, the reactor temperature decreased towards the temperature of the raw feed. The decrease in temperature can be seen to occur after approximately 1800 h in Figure 31.

In full-scale field systems, temperature changes of interest would include those due to seasonal changes or to precipitation and infiltration. The RTD temperature detector used here can be expected to give trouble-free operation with correct installation and initial calibration.

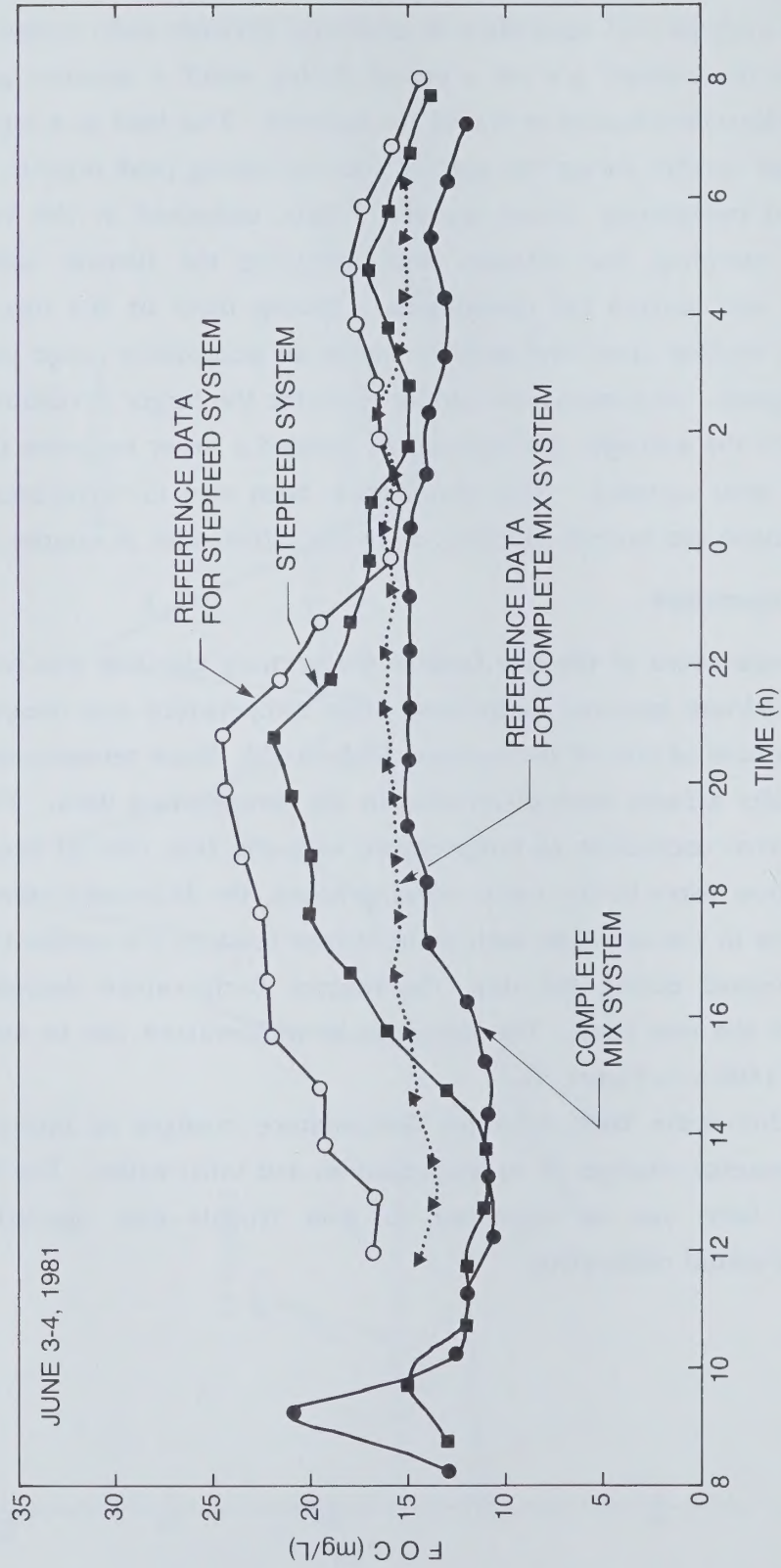


FIGURE 30 ON-LINE FILTERED ORGANIC CARBON MEASUREMENTS COMPARED WITH REFERENCE DATA

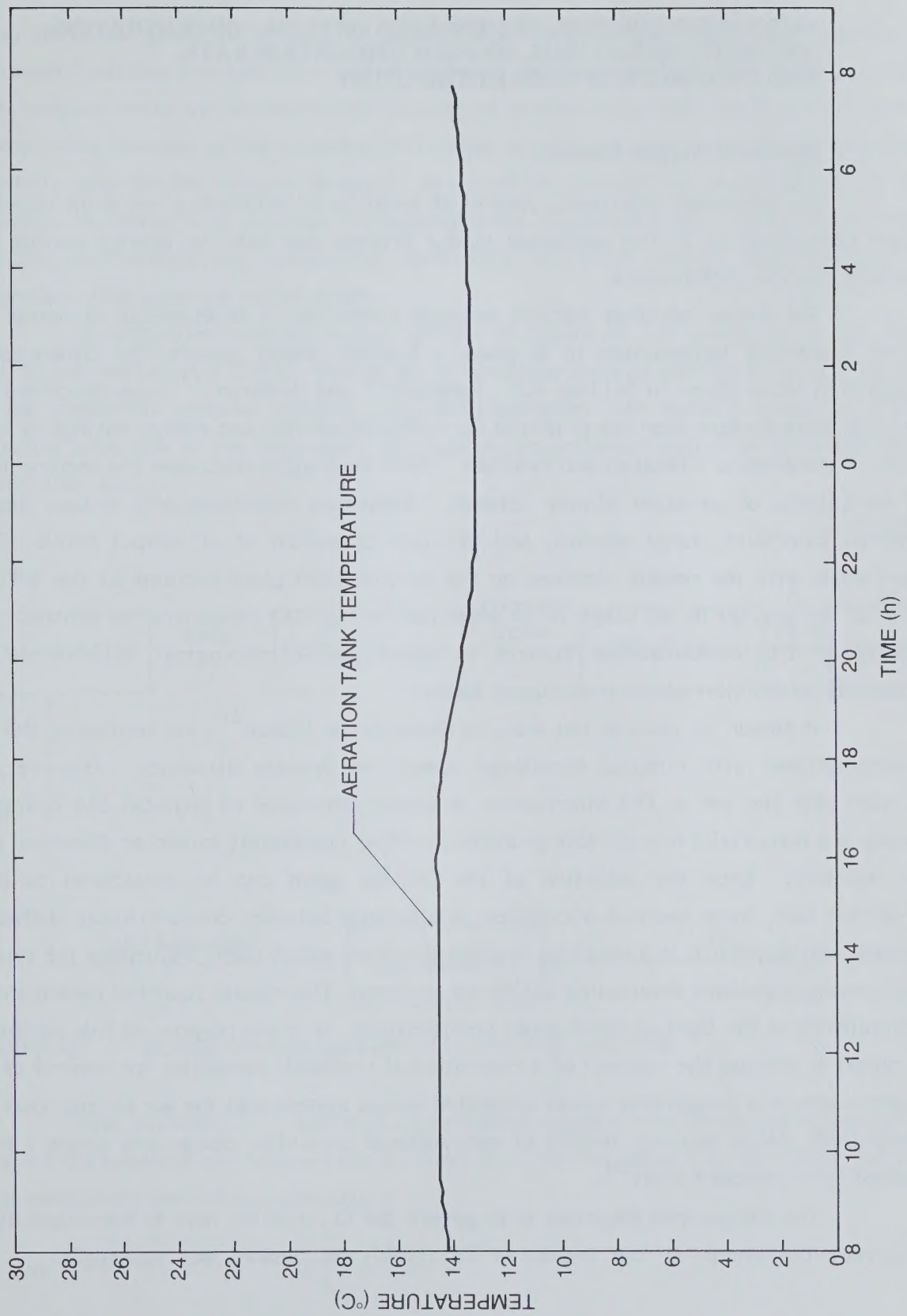


FIGURE 31 ON-LINE AERATION TANK TEMPERATURE MEASUREMENTS DURING 24-h PERIOD

5 AUTOMATIC CONTROL OF DISSOLVED OXYGEN CONCENTRATION, SOLIDS RETENTION TIME, OXYGEN UTILIZATION RATE, AND DYNAMIC STEP FEED DISTRIBUTION

5.1 Dissolved Oxygen Control

As previously discussed, control of aeration to maintain a set point dissolved oxygen concentration in the activated sludge process can lead to energy savings and improved process performance.

To design aeration control systems correctly, it is essential to assess the factors governing oxygenation in a plant. Factors which govern the dynamics of oxygenation were given in Section 4.2. Sørensen¹⁸ and Anderson¹¹ have described the effect of these factors upon the potential for efficient control and energy savings in some detail. Furthermore, Flanagan and Bracken¹⁹ have thoroughly discussed the requirements and limitations of aeration blower control. Important considerations include blower turndown capability, surge control, and efficient operation at all output levels. This report deals with the results obtained on the parallel pilot plant systems at the WTC in terms of the savings in air usage to be expected through DO concentration control. The coupling of DO concentration control to estimation of biological activity in the completely mixed pilot plants is discussed later.

It should be pointed out that, as discussed by Olsson¹⁷, the control of DO can be accomplished with minimal knowledge about the process dynamics. However, he indicates that the use of DO information to obtain estimates of physical and biological activity is a non-trivial but solvable problem in either completely mixed or dispersed plug flow reactors. Even the selection of the DO set point can be considered to be a non-trivial task, since there is a complex relationship between concentration, diffusion, reaction, and dispersion in a respiring biological system which likely influences the type of floc-forming organisms dominating within the process. The results reported herein should be considered in the light of these other complexities. It is the purpose of this section of the report to discuss the concept of a conventional feedback controller for control of DO concentration in a completely mixed activated sludge system and the air savings that can be expected. More thorough details of conventional controller design and tuning can be obtained from standard texts²⁰.

The DO control objective is to govern the O_2 transfer rate to the mixed liquor to correct deviations of the measured DO from the desired set point, DO_{sp} . At

steady-state all rates of change of process variables are zero; however, wastewater treatment facilities are subject to significant load and operating changes. The principles of O_2 requirements for synthesis and respiration dictate that these changes will lead to corresponding changes in the measured DO unless the oxygen transfer rate is manipulated to satisfy exactly the oxygen demand. It would be difficult or impossible to do this manually. However, it is possible to manipulate the O_2 transfer rate using commercially available instrumentation, automatic controllers and final control elements such as compressor inlet vanes or motor speed.

A simplified control loop is shown in Figure 32 for manipulation of motor speed to control DO in a CSTR. Two types of controller, analog and digital, are in general use for industrial process control. Digital controllers are rapidly outpacing analog controller sales due to the decreasing price of microprocessors and their wide flexibility in controller design.

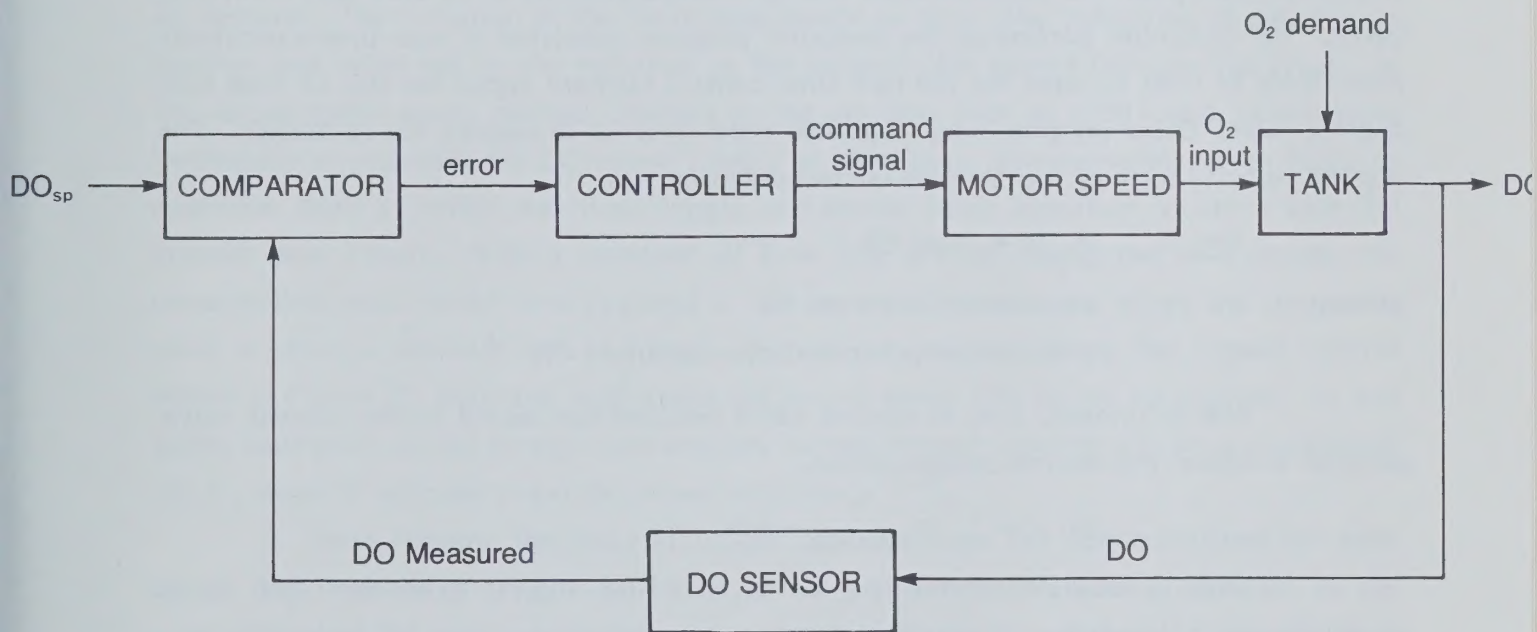


FIGURE 32 BLOCK DIAGRAM FOR DO CONTROL SYSTEM

The literature^{7,21} and WTC experiences suggest that feedback proportional-integral (PI) control can be used for DO control. The form that this controller can take is represented by the following equation.

$$\Delta m = K_p \cdot e + \frac{1}{K_I} \int_0^t e dt$$

where: Δm = change in final control element (e.g. valve position, motor speed)
 e = $DO_{sp} - DO_{measured}$
 t = time
 K_p = proportional gain
 K_I = integral time

The above equation specifies that a change in the final control element, Δm , is proportional to the sum of the deviation from the setpoint, e , and the time integral of the deviation. Using this controller the steady-state error can be forced to tend towards zero. Through appropriate selection of K_p and K_I , a stable controller can be applied which minimizes DO variations through incremental changes in the final control element.

At the WTC the PI controller has been implemented on a digital minicomputer to control pilot plant DO concentration through manipulation of an air flow rate throttling valve. The controller portion of the computer program consisted of real-time executable FORTRAN IV code to solve for the new final control element signal for the air flow rate control valve. Other programming steps also were involved to support the controller. The applied velocity form of the discrete control equation was:

$$\Delta m = K_p (e - e_1 + e \Delta t / K_I)$$

where: Δt = discrete control interval
 e_1 = previous set point deviation at time $t - \Delta t$

The increment, Δm , in control valve position was added to the current valve position to obtain the desired control action,

$$m = m_{current} + \Delta m$$

This is easily implemented on a real-time digital processor such as a minicomputer. Although a conventional PI control algorithm was used for control, it was not necessarily the optimum controller choice. Efforts have been made in recent years to use adaptive self-tuning controllers. These controllers have the advantage of providing controller parameters that reflect process information such as O_2 transfer efficiency and oxygen utilization rate in a recursive manner. Significant efforts should be directed to the efficient development and application of these modern controllers in wastewater treatment. Such efforts were beyond the scope of the present study.

The digital PI controller gain was 1.9, corresponding to a proportional band of 53%, significantly lower than reported values of 200 to 250% for a full-scale aeration system which included blower control²¹. The integral time was 0.25 h. Based on trial tests, five seconds was chosen as the DO sample interval and 60 seconds as the control interval. Thus, the average of 12 DO measurements was available at each control interval. Air flow rate to the manually controlled plant was manipulated periodically during the day (0800 to 1800 h) by manual means in an attempt to maintain a minimum DO of 1.0 mg/L. The operator had the advantage of on-line DO measurements for regulating the uncontrolled plant air flow rate.

Figure 33 depicts the 15-minute average DO response to a typical diurnal variation in hydraulic and organic loading. Effective control of the DO to a 2 mg/L set point was achieved in the controlled plant. The DO concentration can be seen to be slightly depressed during rapid increases in air demand and elevated during decreases in air demand. The variation in the controlled plant's air flow rate, indicative of the process loading, was reflected by the variation in the uncontrolled plant's DO concentration. In the uncontrolled plant, manual changes in the air flow rate at 1300 h and 1800 h were inadequate to maintain the DO above 1 mg/L at all times. Approximately seven hours of operation were at levels less than 1 mg/L and eleven hours operation occurred with DO greater than 2 mg/L. With a constant air flow rate setting during the 24-h period, the uncontrolled plant would have required a 70% increase in air supply above the controlled plant to meet a minimum DO of 2 mg/L at the peak loading. Using the manual control shown in Figure 33, potential still exists for saving about 35% of the air applied. At full scale, savings in actual energy consumption through blower control will be a function of the O_2 transfer efficiency and the blower efficiency^{11,19}.

Data showing the daily minimum and maximum DO concentrations for both plants are depicted in Figure 34 for a 130-day period. The actual variation in the controlled plant DO consistently behaved as shown in Figure 33 and the extremes shown in Figure 34 were usually brief and due to extraneous factors. For the uncontrolled plant, minimum and maximum DO values were approached and maintained for significant intervals. Even with persistent adjustments in the manual air flow rate setting, this plant frequently exhibited minimum DO concentrations less than 1 mg/L. From an energy viewpoint, significant air wastage was observed, with maximum DO's approaching saturation. The peaks and troughs in mean daily DO's in the uncontrolled plant occurred within seven days, coincident with weekly cycles in the plant loading. Thus, DO control must take into account daily and weekly variations in oxygen demand and mixing needs.

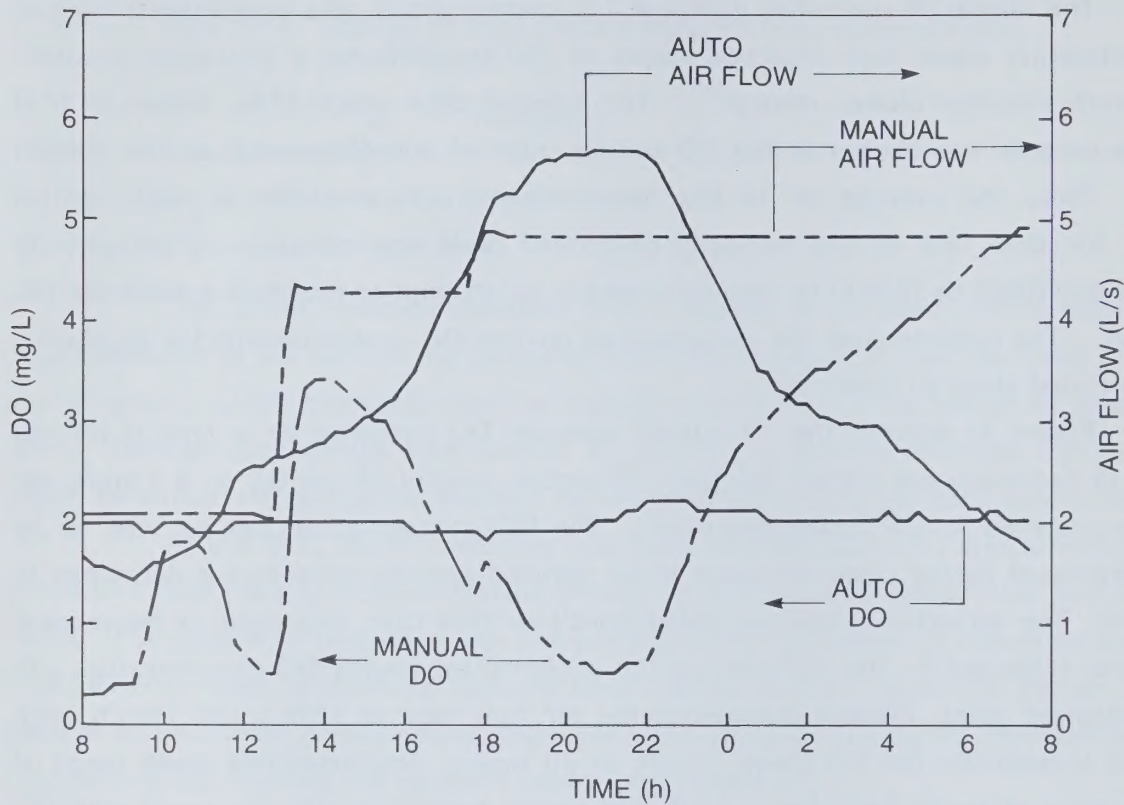


FIGURE 33 DISSOLVED OXYGEN CONCENTRATIONS AND AIR FLOW RATES DURING 24 h FOR AUTOMATICALLY AND MANUALLY CONTROLLED PLANTS

Throughout the DO control period, the manually operated plant had a standard deviation in the DO concentration of 0.9 mg/L. In comparison, the standard deviation of the DO concentration in the automatically controlled plant was 0.2 mg/L at the set point of 2.0 mg/L. At the 4.0 mg/L set point the standard deviation was 0.1 mg/L.

The DO of the uncontrolled system approached saturation concentration almost every day of operation at the trough in diurnal plant hydraulic and organic loadings, whereas the automated system DO was controlled at the set point (Figures 33 and 34). The high DO's maintained in the manual system at these times directly affected energy requirements as shown by the relative demand for air delivery at various DO set points and saturation concentrations (Figure 35). Highest transfer efficiency is maintained with the highest driving force possible at zero mg/L DO. This, however, is not usually the most desirable operating concentration but nor is the saturation concentration. Because of the relationship between air flow rate and power consumption, significant

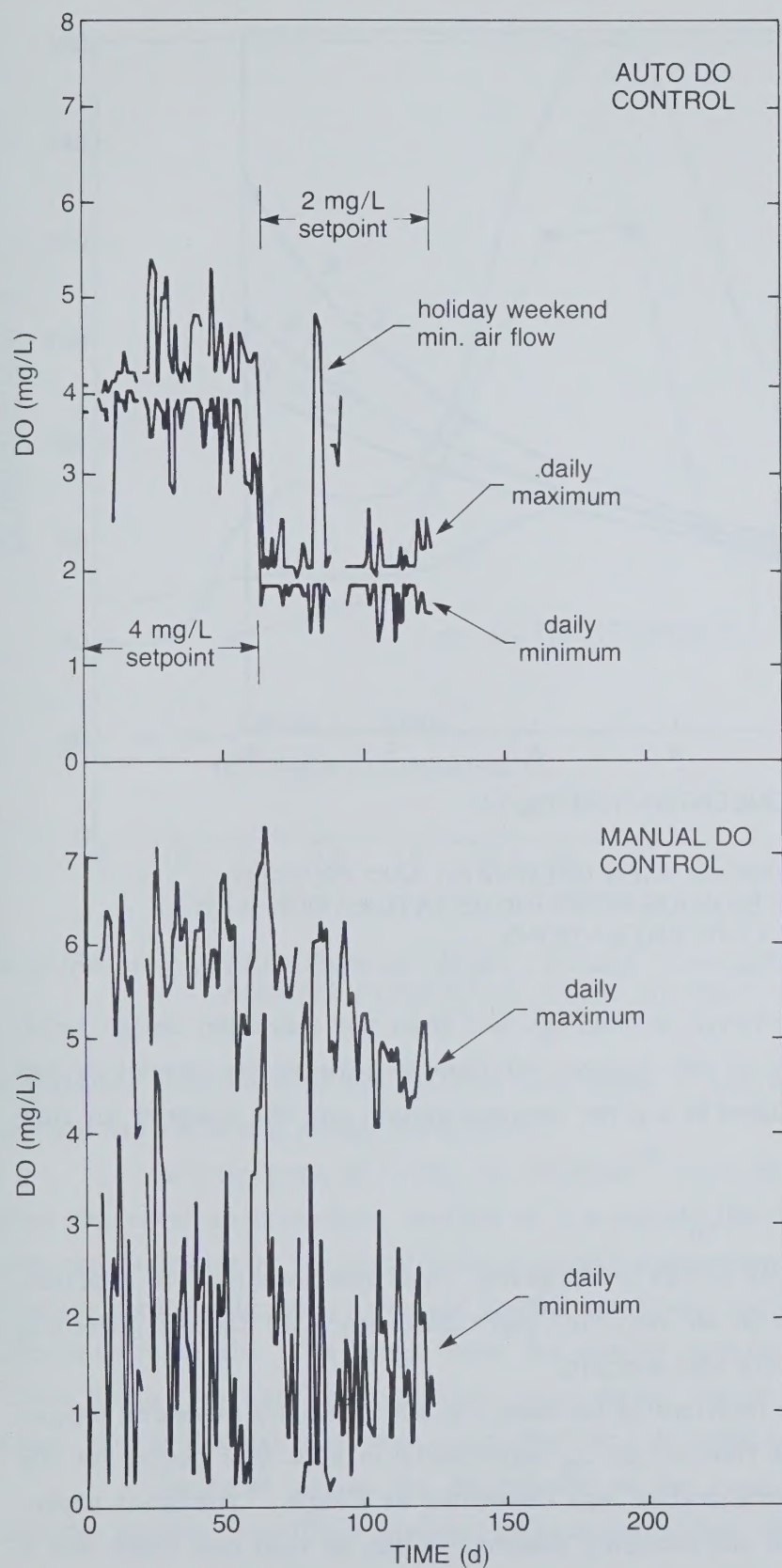


FIGURE 34

DISSOLVED OXYGEN FOR AUTOMATICALLY AND MANUALLY CONTROLLED AERATION SYSTEMS

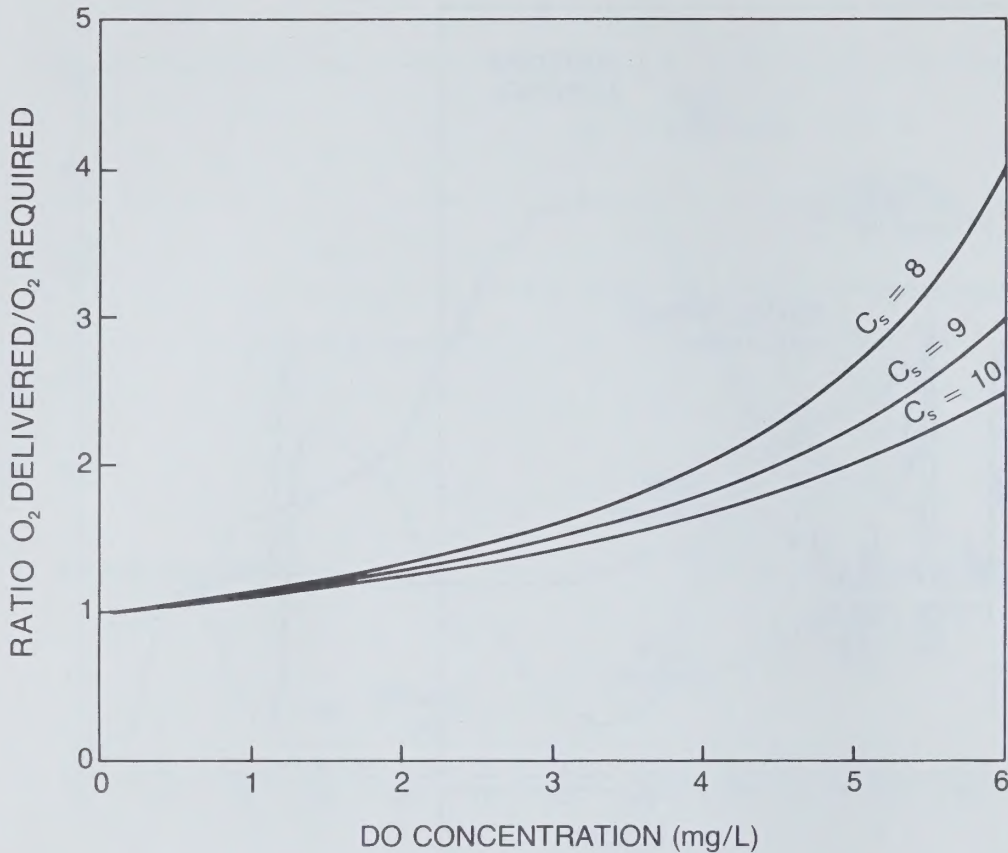


FIGURE 35 RATIO BETWEEN OXYGEN DELIVERED AND OXYGEN REQUIRED BY BIOMASS AT VARIOUS SATURATION AND REACTOR DO CONCENTRATIONS

savings in air supply can be achieved at loadings less than the maximum design level. These savings will be a function of the dynamic relationship between the overall oxygen transfer coefficient ($K_L a$) developed by a given aeration system and the power or air flow (Q_a) delivered:

$$K_L a = f(Q_a)$$

The WTC is currently (1982) investigating these relationships. In practice, cost savings must be evaluated on an individual plant basis since all factors governing savings, including energy costs, are site-specific.

Figure 36 shows the relationship between the automatically measured oxygen transfer, air flow, and substrate removal (in O_2 equivalents) in a 24-hour period for the Burlington pilot plant. DO concentration was controlled at 2 mg/L. The plant experienced diurnal variations in flow and substrate loading. It can be seen that there was a

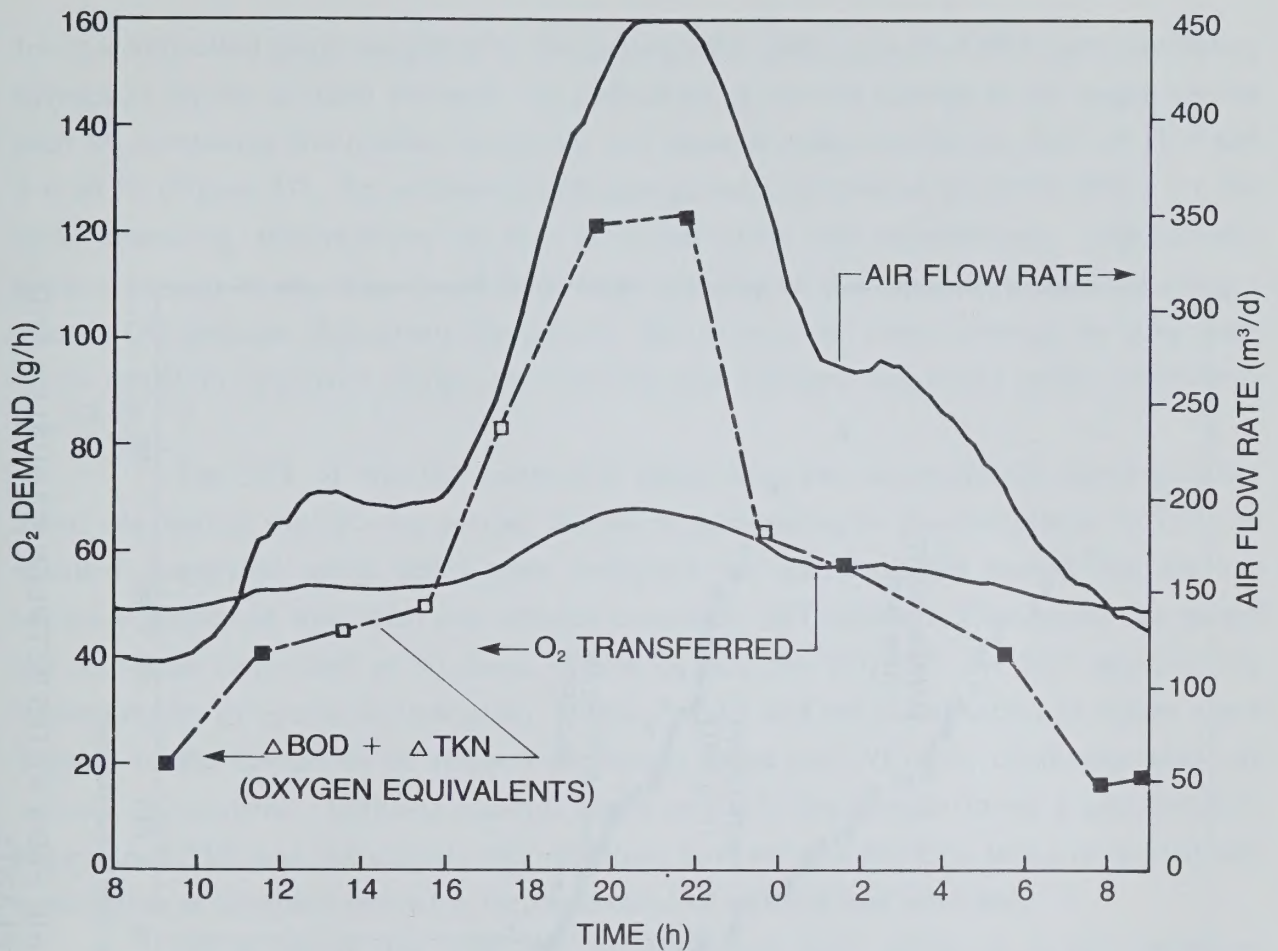


FIGURE 36 RELATION BETWEEN OXYGEN TRANSFER, SUBSTRATE REMOVAL, AND AIR FLOW RATE UNDER DIURNAL LOADING CONDITIONS

significant difference in the relative amplitudes of the air flow rate required for DO control and the actual oxygen transferred.

Investigations by Clifft and Andrews²² have shown that the substrate loading does not exert an immediate demand on the oxygen transfer, and is not necessarily an accurate indicator of the instantaneous oxygen requirement. Rather the oxygen requirement is a good indicator of average loading conditions and can be used to estimate plant substrate removals. The areas under the oxygen transfer curve and substrate removal curve (Figure 36) were approximately equal during the 24 hours thus representing equal mass. Similar findings have been established for full-scale systems²².

Figure 37 shows the distribution of the mean daily air flow rates for the 130-day period. Significant savings (~29%) in the median value of air applied were evident

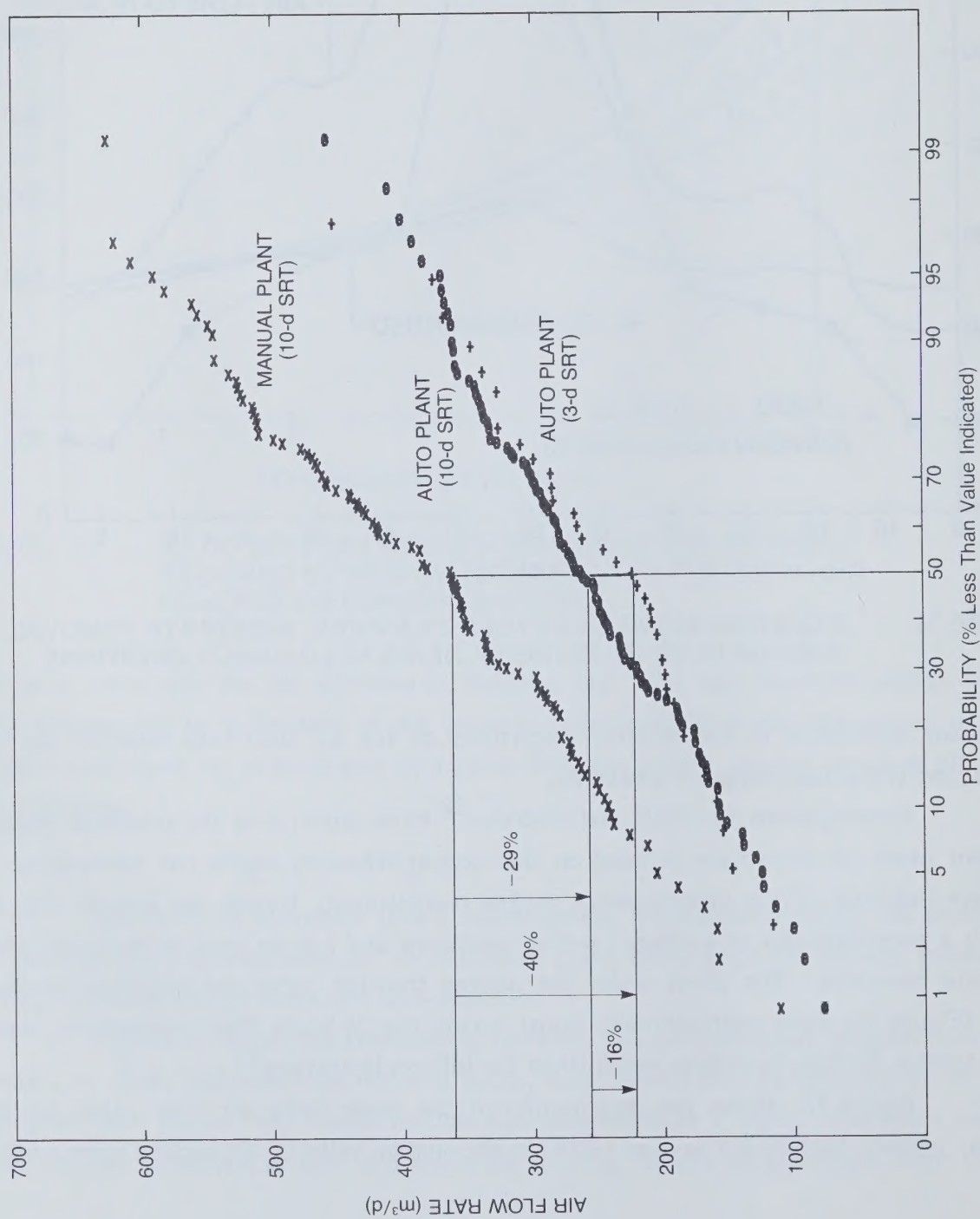


FIGURE 37 DISTRIBUTIONS OF MEAN DAILY AIR FLOW RATES BETWEEN MANUALLY AND AUTOMATICALLY CONTROLLED PLANTS

for the controlled plant compared to the uncontrolled plant at a 10-d SRT, with increasing savings at higher air flow demand. An indication of further savings in air usage can be seen by comparing the median values for the automatically controlled plant at 10-d and 3-d SRT's (Figure 37). An additional 16% saving was indicated at the lower SRT. At the 15°C operating temperature, no loss of nitrification was experienced. Significantly greater savings in air usage could have been attained in the controlled plant by using a 2 mg/L DO setpoint throughout the period. DO control and lower average air flow rates could result in improved sludge settleability and effluent suspended solids concentration^{23,24}.

The SRT of the DO-controlled plant also was automatically controlled for about one-half of the 130-day period. Paired data between the parallel plants for SVI and effluent suspended solids (ESS) were analyzed for the combined period and for the separate periods of time with and without automatic SRT control. Throughout the period the SRT was controlled at 10 days. Table 19 lists the SVI, ESS and SRT data for the various modes of operation indicated. Modes 1 and 2 and the combination of modes 1 and 2 apply to the discussion of effluent suspended solids and SVI under conditions with and without DO control. Effluent quality, based on 24-h flow-proportioned gravimetrically determined ESS, was not statistically different between the plants in terms of day-to-day mean value or standard deviation for the individual or combined data sets.

Up to about day 130, the parallel plant SVI's appeared to be correlated (Figure 38); however, the DO-controlled plant had a significantly lower value and less variability based on the data for mode 1 and the combined data (Table 19). Although difficult to verify with the available data, automatic DO control appears to damp variations in SVI to some extent. This may have some foundation based on the effect of DO levels on sludge settleability²³.

Full scale work conducted by Wells at Fairfield, California dealing with DO control also showed significant improvement in sludge settleability (SVI) and the prevention of bulking between parallel trains with and without DO control²⁵. In the Fairfield case, only one clarifier was required for the DO control case versus two for the uncontrolled case.

5.2 Solids Retention Time Control

Current trends in activated sludge process control suggest that SRT (also called sludge age, or mean cell retention time) control is one of the most suitable techniques available to the plant operator. This strategy is equivalent to long-term

TABLE 19 PAIRED COMPARISON OF PARALLEL PLANTS UNDER DIFFERENT OPERATING MODES

MEAN VALUES $\pm$ STANDARD DEVIATION																	
Operation Mode	A-Plant		B-Plant		Target SRT [†] (d)	SRT(d)		SVI (mL/g)				ESS (mg/L)					
	DO	SRT	DO	SRT		A	B	Sign.*	N(d)	A	B	Sign.*	N(d)	A	B	Sign.*	N(d)
1	✓	x	x	x	10	10.5 $\pm$ 1.5	9.9 $\pm$ 1.8	Yes	55	151 $\pm$ 102	211 $\pm$ 130	Yes	49	11 $\pm$ 9	10 $\pm$ 8	No	52
2	✓	✓	x	x	10	10.0 $\pm$ 1.9	10.5 $\pm$ 2.3	No	67	211 $\pm$ 128	230 $\pm$ 156	No	82	15 $\pm$ 12	17 $\pm$ 14	No	73
1 & 2 combined	✓	-	x	x	10	10.2 $\pm$ 1.7	10.3 $\pm$ 2.1	No	122	188 $\pm$ 116	223 $\pm$ 147	Yes	131	13 $\pm$ 11	14 $\pm$ 12	No	125
4	✓	✓	✓	x	3	2.8 $\pm$ 0.4	3.0 $\pm$ 0.4	No	39	106 $\pm$ 68	288 $\pm$ 279	Yes	42	22 $\pm$ 17	21 $\pm$ 14	No	42
5	✓	OUR**	✓	✓	3	3.5 $\pm$ 4.1**	3.3 $\pm$ 0.9	N/A	38	145 $\pm$ 92	143 $\pm$ 100	No	47	24 $\pm$ 17	27 $\pm$ 17	Yes	37

* differences between A and B plants determined to be significant (Sign.) based on N days of paired data.

** A-plant solids inventory control based on OUR; median SRT value reported rather than mean.

✓ automatic control

x manual control

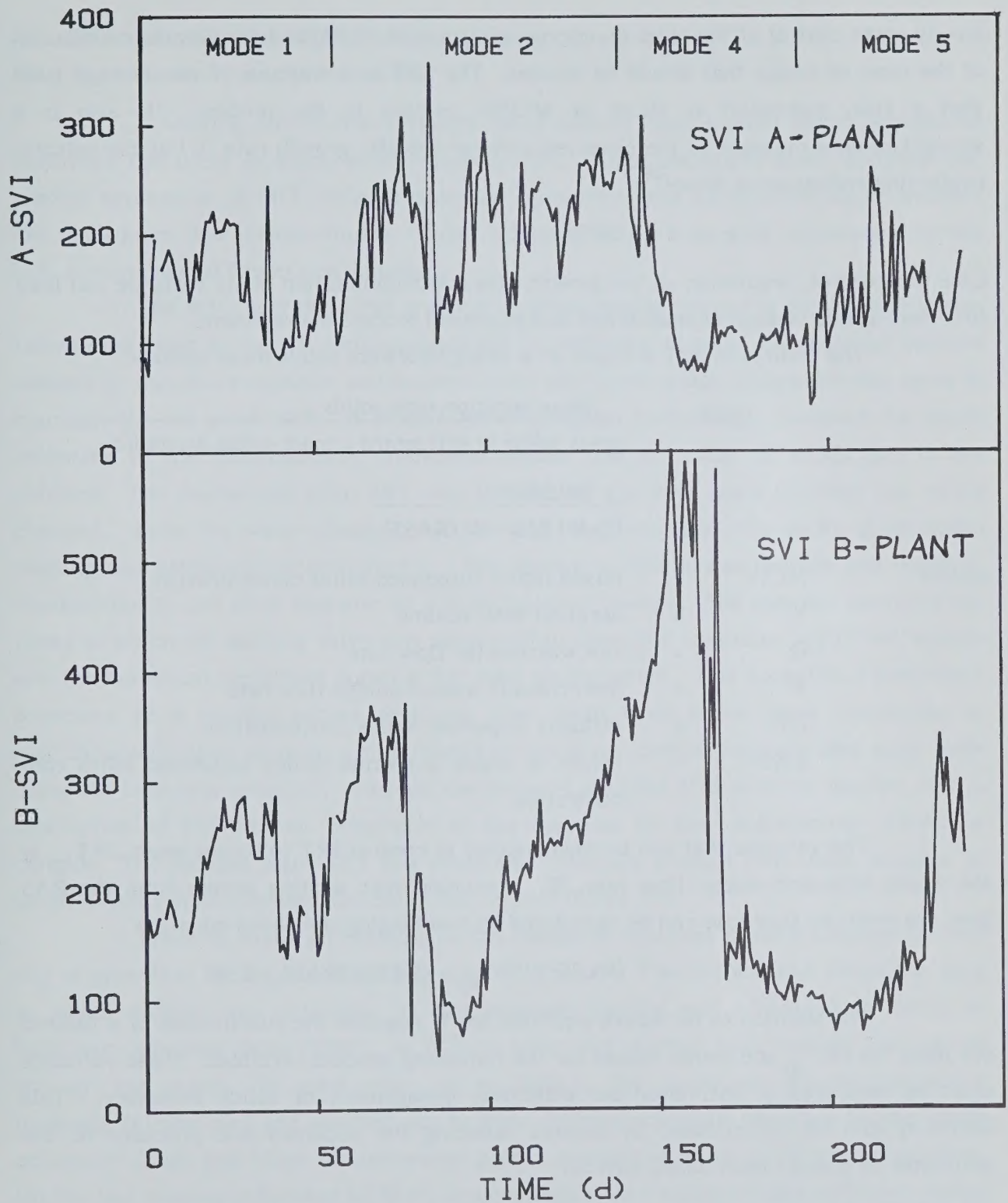


FIGURE 38 SVI'S OF PARALLEL PLANTS FOR DIFFERENT MODES OF OPERATION

steady state control of the food-to-microorganism ratio (F/M) and permits the calculation of the mass of sludge that should be wasted. The SRT is a measure of the average time that a floc, expressed as MLSS or MLVSS, resides in the process. It also is a straightforward measure of the observed average specific growth rate (μ) of the culture, neglecting endogeneous decay²⁶:

$$\mu = \text{SRT}^{-1}$$

Like DO control, regulation of the growth rate and minimization of its variance can lead to a more stable biological equilibrium and improved process management.

The control of SRT is based on a straightforward solids mass balance:

$$\begin{aligned} \text{SRT} &= \frac{\text{Mass aeration tank solids}}{\text{mass solids in effluent/d} + \text{mass solids wasted/d}} \\ &= \frac{(\text{MLSS})V}{(Q-W) \text{ESS} + W (\text{RASS})} \end{aligned}$$

where:

MLSS	=	mixed liquor suspended solids concentration
V	=	aeration tank volume
Q	=	raw wastewater flow rate
W	=	intentionally wasted sludge flow rate
ESS	=	effluent suspended solids concentration
RASS	=	return or waste activated sludge suspended solids concentration.

The variable that can be manipulated to control SRT to its set point, SRT_{sp} , is the waste activated sludge flow rate, W. Assuming that wasting occurs from the RAS line, the required flow rate can be calculated by rearranging the above equation

$$W = (\text{MLSS} \cdot V / \text{SRT}_{sp} - Q \cdot \text{ESS}) / (\text{RASS} - \text{ESS})$$

The solution to the above equation for W requires the substitution of a desired set point for SRT_{sp} and known values for the remaining process variables. These variables must be measured or estimated for effective management of solids inventory. This necessity can be complicated by factors reducing the accuracy and precision of the estimates on a short term basis, such as:

- i) RASS changes with hydraulic loading to the system, variable RAS flow rate, changes in settleability, clarifier rake position, or wasting itself.

- ii) ESS varies significantly with time.
- iii) Q or W may be poorly measured.

If wasting occurs intermittently, as it does at many smaller plants, significant variations can occur in waste solids concentration. These variations make accurate and precise estimation of SRT difficult based on infrequent grab samples for solids analyses and inadequate flow measurements. These difficulties have been well documented by the U.S. Environmental Protection Agency¹.

The WTC addressed this problem by investigating the use of on-line instrumentation interfaced to the HP minicomputer and its software to solve the material balance defined by the above equation and to control the pilot plant waste sludge solenoid valve to maintain the set point SRT. A FORTRAN IV program continuously assessed the solids inventory in the automatically controlled system and the mass of solids lost in the effluent. The desired set point SRT was entered by the pilot plant operator but rarely changed. Since the waste sludge flow rate was relatively small due to the plant scale, wasting was performed intermittently. The wasting schedule was flexible and could be manipulated by the plant operator at a minicomputer console. The operator specified the times at which the wasting valve was permitted to open, the maximum permitted volume and the maximum permitted duration for each waste period. This operational judgement overcame to a certain extent problems that could have arisen from inaccurate or malfunctioning plant sensors. Other checks of signal and process integrity also were made using the computer program. Various alarms were sounded if a problem existed with a description of the problem presented to the operator on the minicomputer printer or console. The parallel plant SRT was controlled manually through continuous wastage of solids directly from the aeration tank until mode 5 (Table 19).

Table 20 shows an example of the computer reported wasting progress for one day of operation for the automatically controlled plant. The first column shows the time at which wasting was initiated. In this example wasting was scheduled to occur at half-hour intervals from 0300 h to 0730 h after the diurnal peak loading had passed through the plant. In each case up to 0600 h, the maximum volume constraint (message 14) was met and wasting was halted. On two occasions (message 5), the waste activated sludge fell below an arbitrarily preset concentration thus halting the wasting. On the last wasting scheduled (0730 h), no constraints were exceeded and sufficient sludge was wasted to achieve the set point SRT of three days. A daily wasting period was

TABLE 20 PLANT WASTING SCHEDULE BASED ON SRT CONTROL,
SEPTEMBER 9, 1980

Time (h)	Volume Wasted (L)	System Mass (g)	Unintentional Waste (g)	Intentional Waste (g)	Message
0300	50	4 970	151	202	14
0330	100	4 970	152	390	14
0400	150	4 970	153	566	14
0430	200	4 970	154	734	14
0500	240	4 960	155	867	14
0530	290	4 960	156	1 020	14
0600	340	4 940	157	1 160	14
0630	390	4 930	157	1 290	5
0700	429	4 910	158	1 400	5
0730	452	4 820	160	1 470	0
Actual SRT	=	3.00 d			
Equilibrium SRT	=	3.00 d			
Set point SRT	=	3.00 d			

calculated starting at 0800 h. This summary proved useful from an operating viewpoint. In the event that a sudden shift in the instantaneous SRT occurred, a calculation was automatically performed to estimate the actual equilibrium SRT. The result was displayed to the plant operator as shown in Table 20. The following equation was used to calculate the equilibrium SRT:

$$SRT_{eq} = SRT (e^{-\Delta t / \Delta SRT})$$

where: Δt = time elapsed in days from previous calculation, usually one day.

ΔSRT = difference in measured SRT during elapsed time.

Figure 39 depicts the gravimetrically determined instantaneous SRT's for the automatically and manually controlled plants throughout the experimental period described in Table 19. SRT set points for the automatic SRT control phases of the program were 10 days for mode 2 (days 57 to 141) and 3 days for mode 4 (days 150 to 193).

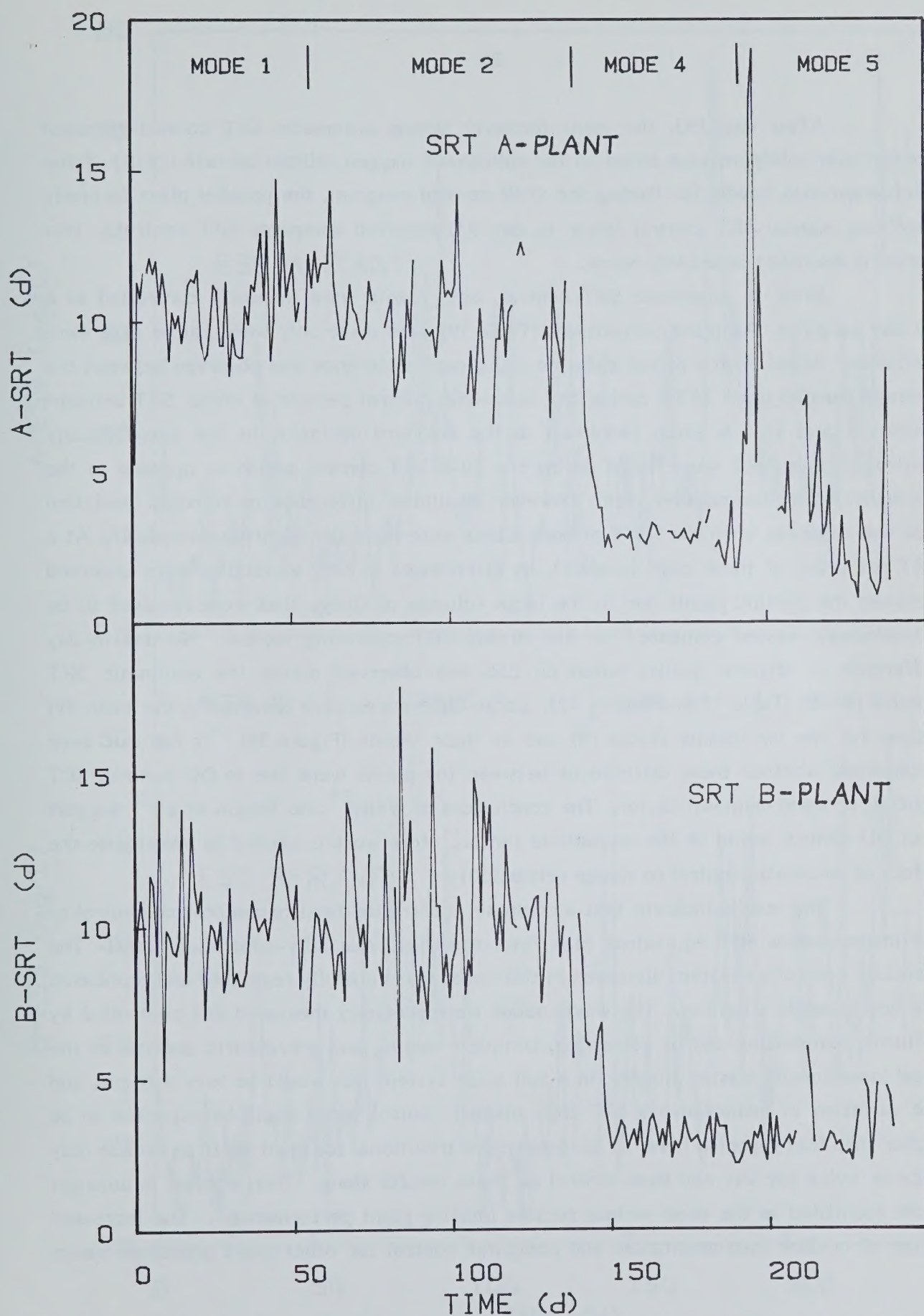


FIGURE 39 GRAVIMETRICALLY DETERMINED INSTANTANEOUS SRT'S FOR PARALLEL PLANTS

After day 193, the plant formerly having automatic SRT control received control over solids wastage based on the volumetric oxygen utilization rate (OUR) of the microorganisms (mode 5). During the OUR control program, the parallel plant formerly receiving manual SRT control (prior to day 93) received computer SRT control. This period is discussed separately below.

Prior to automatic SRT control, both plants were manually controlled at a 10-day set point. All plant comparisons (Table 19) were made only when paired data were available. Based on the paired data, no significant difference was observed between the average parallel plant SRT's during the automatic control periods at either SRT setpoint (modes 2 and 4). A small reduction in the standard deviation of the automatically controlled plant SRT was evident during the 10-d SRT control period as opposed to the manually controlled parallel plant; however, a similar difference in standard deviation also was observed when the SRT's of both plants were manually controlled (mode 1). At a SRT set point of three days (mode 4), no differences in SRT variability were observed between the parallel plants due to the large volumes of sludge that were required to be intentionally wasted compared to the 10-day SRT operating modes. No day-to-day difference in effluent quality based on ESS was observed during the automatic SRT control phases (Table 19 and Figure 40). Large differences were observed in the mean SVI values for the two plants (Table 19) and in their trends (Figure 38). It has not been determined whether these differences between the plants were due to DO control, SRT control, or some unknown factor. The conclusions of Wells²⁵ and Sezgin et al.²⁷ suggest that DO control would be the responsible factor. More work is needed to investigate the effect of automatic control on sludge settleability.

The results indicate that a computer-controlled facility can provide control of the instantaneous SRT equivalent to a "well-operated" manually-controlled plant. The manually controlled system discussed in this paper was carefully regulated and represents the best possible situation. The waste solids were precisely measured and controlled by effluent compositing and by collection, complete mixing and gravimetric analysis of the total intentionally wasted sludge. In a full scale system this would be very difficult and the variation in instantaneous SRT in a manual control mode could be expected to be higher than that reported here. It has been more traditional for plant staff to sample only once or twice per day and base control on these results alone. This problem is amongst those identified as the most serious factors limiting plant performance¹. The increased usage of on-line instrumentation and computer control for other plant processes means

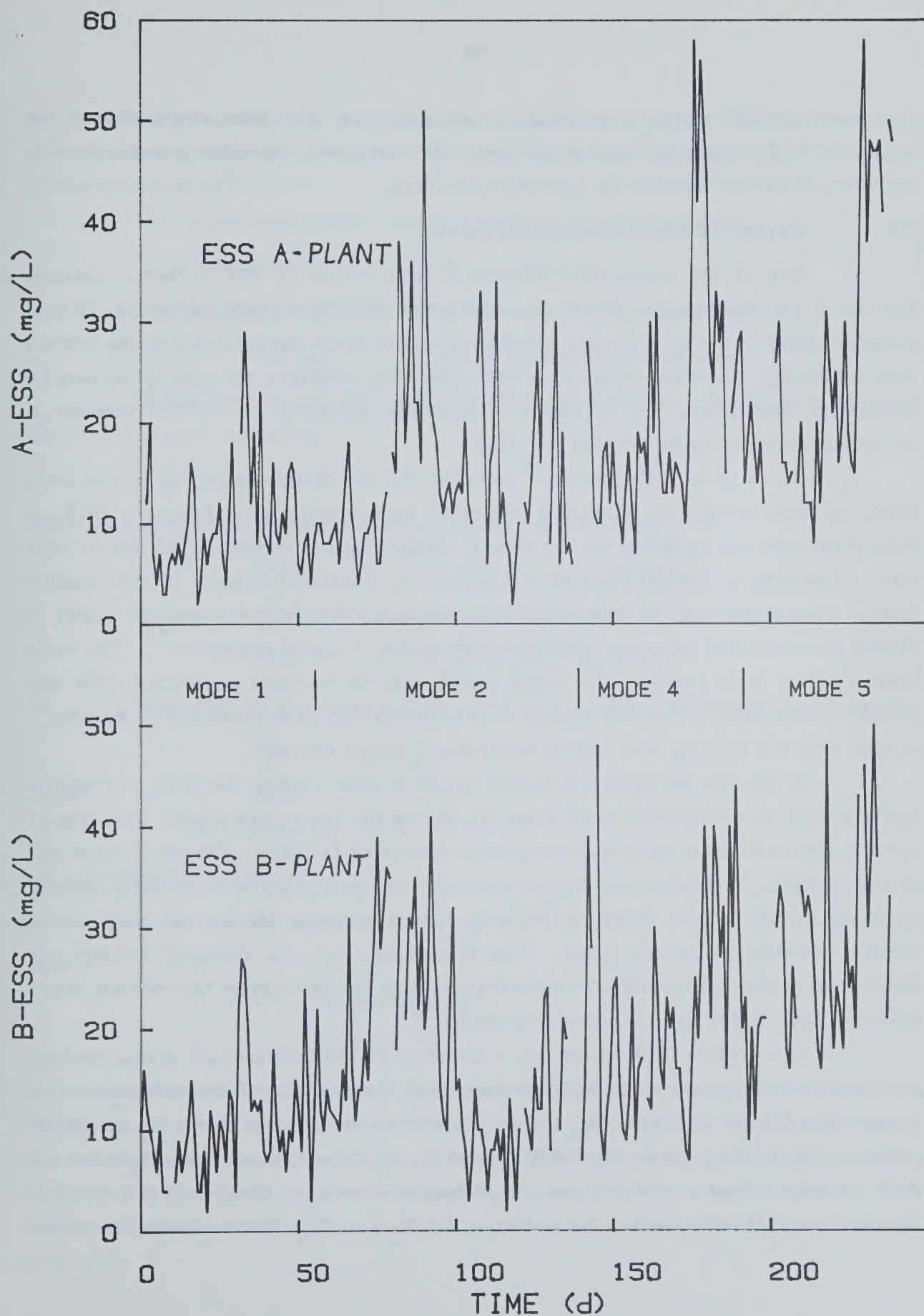


FIGURE 40

GRAVIMETRICALLY DETERMINED EFFLUENT SUSPENDED SOLIDS
FOR PARALLEL PLANTS

that automatic SRT control capabilities do and will exist. Full scale verification of the automatic SRT control strategy in parallel with a manually operated process train is necessary to further examine the control implications.

5.3 Oxygen Utilization Rate (OUR) Control

One of the assumptions inherent in the control of SRT is that a constant fraction of the mixed liquor volatile suspended solids (MLVSS) is viable and active. This is probably closer to the truth in pure culture systems to which the activated sludge process does not belong. Under non-optimum or toxic operating conditions the assumption may be completely inadequate. It is, however, generally accepted that active biomass is accurately indicated by the level of the OUR.

As early as 1969 Brouzes²⁸ reported the use of volumetric O_2 uptake rate, OUR, for monitoring and controlling activated sludge systems in France. OUR or respiration rate was measured on-line through controlling and measuring DO and air flow rate. Knowledge of the oxygenation capacity or O_2 transfer efficiency of the aeration system allowed OUR to be calculated automatically. At present about 100 plants in France are controlled using this technique with analog or digital equipment²⁹. The basic control action is to regulate the waste sludge rate to maintain a selected OUR and specific growth rate. A limited amount of information has been presented by Brouzes²⁸ to show that this strategy does reduce variations in the growth rate.

In the case of repetitive diurnal cycles in plant loading the OUR corresponds approximately to endogenous respiration rate during the low loading period. This type of cycle is very common in municipal wastewater treatment facilities. The exact cycle will be site specific. In general, low organic and hydraulic loadings occur in the early morning hours, e.g., 0300-0600 h. Sharp increases in diurnal hydraulic loading can lead diurnal organic increases by several hours. This is generally true for domestic activity but difficult to predict. High NH_4 -N concentrations may predominate in the morning hours between 0600-1000 h, but this also is site specific³⁰.

To calculate OUR on-line for a completely mixed diffused air system several process parameters must be estimated or measured. These include DO concentration (C), temperature (T), air flow rate (Q_{air}), feed (Q) and recycle (R) flow rates, O_2 saturation concentration in the process effluent (βC_s), and the O_2 transfer coefficient ($K_L a$) for the field aeration system under process conditions, and aeration tank fluid volume (V). Temperature correction factors are necessary for $K_L a$ and C_s . For methods, limitations

and problems which can be encountered in estimating $K_L a$, the document recently published by the U.S. EPA entitled "Workshop Toward an Oxygen Transfer Standard" should be consulted³¹.

An oxygen mass balance can be written for the aeration tank:

$$O_2 \text{ accumulation} = O_2 \text{ inputs} - O_2 \text{ outputs}$$

If the DO concentration is negligible in the feed and recycle streams then

$$VdC/dt = K_L a \cdot V(\beta C_s - C) - OUR' - (Q+R) \cdot C$$

If the aeration tank DO concentration is controlled to a steady-state set point value as previously discussed,

$$dC/dt = 0$$

and OUR can be calculated after rearranging the above equation,

$$OUR' = K_L a \cdot V \cdot (\beta C_s - C) - (Q+R) \cdot C$$

Volumetric OUR is calculated by dividing through by volume to give

$$OUR = K_L a \cdot (\beta C_s - C) - (Q+R) \cdot C/V$$

In practice $K_L a$ is often a linear function of air flow rate within certain limits:

$$K_L a = m Q_{\text{air}} + b$$

where: m = slope

b = intercept

and a function of temperature:

$$(K_L a)_T = K_{La20} \cdot \theta^{T-20}$$

where: θ = 1.024

T = temperature, °C

$$C_s = 515.28/(T+35)$$

for a given diffused air system with fixed geometry and fluid characteristics. Tests by Sørensen⁷ and the WTC have shown that βC_s is relatively constant in activated sludge effluent and very close to the theoretical value (C_s) for clean water ($\beta \approx 1.0$). Tests must be performed to evaluate the relationship of $K_L a$ to air flow rate in actual systems. For mechanical aeration systems, $K_L a$ could be related to aerator power draw rather than air flow rate.

The process value of $K_L a$ can be affected by air distribution changes, diffuser clogging, surfactants and suspended solids within the process. Sørensen⁷ and Kayser³² have shown that the process $K_L a$ is about the same in a completely mixed activated sludge reactor producing good effluent quality (less than 30 mg/L BOD₅) as in tap water. Also, Boon³³ has shown that $K_L a$ -process/ $K_L a$ -tap water is between 0.8-1.0 at the discharge end of dispersed plug-flow activated sludge reactors. These results indicate that good estimates of the relationship between $K_L a$ -process and air flow rate can be obtained for completely mixed reactors through experimental determinations. Little definitive work has been reported concerning on-line estimation of $K_L a$ -process/ $K_L a$ -tap water. Some excellent indications of the potential of on-line estimation have been given by Holmberg³⁴. More work is needed in this area, particularly to determine time varying and spatially varying values of $K_L a$ -process. The use of self-tuning DO controllers to allow state and parameter estimation on-line is being investigated at the WTC.

Figure 41 shows the experimentally determined relationship between $K_L a$ and air flow rate for the WTC pilot plant during the period of sludge wastage under OUR control. The slope of the relationship shown indicated that large increases in air flow rate would lead to modest increases in O₂ transfer efficiency for this pilot plant over the range of interest. This has important implications in choosing aeration equipment since minimum increases in air flow rate are desirable from an energy viewpoint to meet increases in O₂ demand. Air consumption has a direct impact on plant energy requirements and efficient O₂ transfer is essential.

The solids inventory control period for one of the parallel plants based on OUR (mode 5, Table 19) commenced on day 194 and continued to the study's completion. The other parallel plant was controlled using the automatic SRT approach with a set point of three days.

The above equations were used to calculate the OUR for the pilot plant reactor using the on-line instrumentation interfaced to the minicomputer. OUR was calculated at five-second intervals and averaged at 15-minute intervals using a FORTRAN IV program with real-time extensions. As in SRT control, sludge wasting was programmed to occur after the usual peak loading to the plant in the evening hours. Wasting usually occurred anytime after 0300 h in order to have OUR estimates approaching the endogeneous equivalent by the end of the 24-h period at 0800 h.

The control objective was to limit the sludge wasting to maintain a specific biomass activity in terms of OUR for the expected load during the subsequent day. The

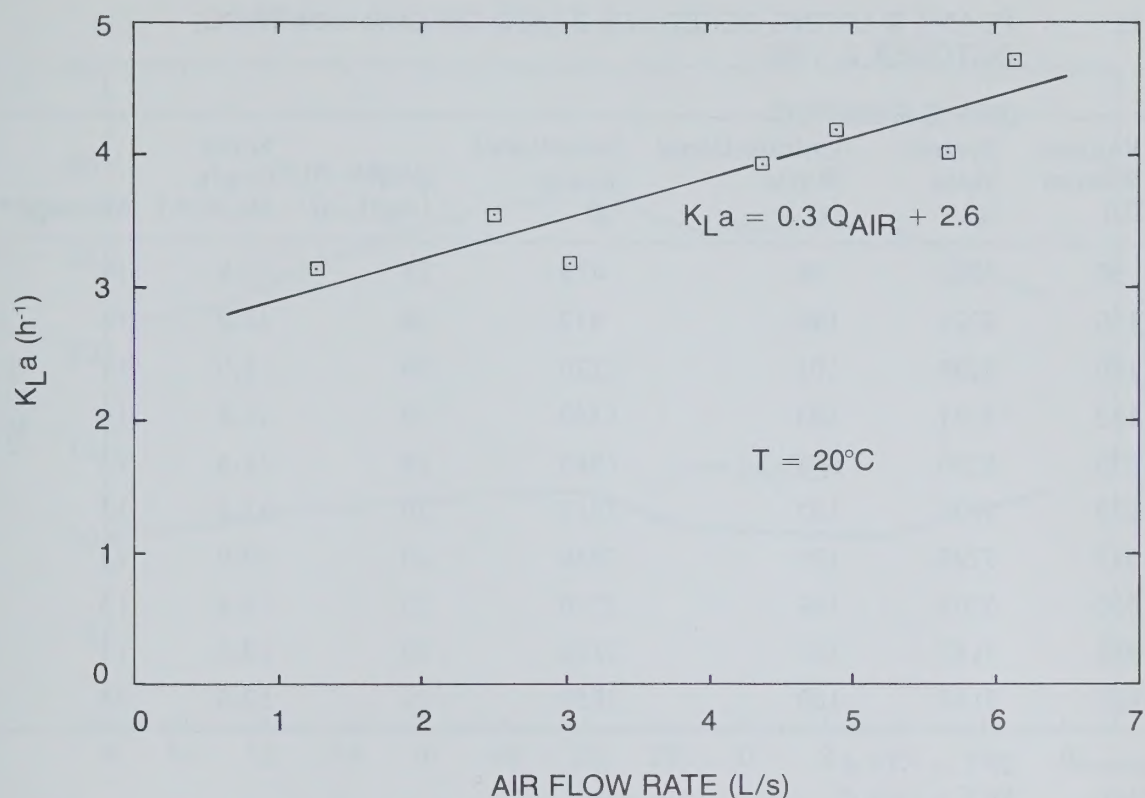


FIGURE 41 RELATIONSHIP BETWEEN $K_L a$ AND AIR FLOW RATE FOR PILOT PLANT

desired set point OUR was selected to provide the degree of biomass activity and substrate oxidation required. The selected set point was determined through examination of previous plant records which showed adequate treatment at a given measured OUR.

For Burlington wastewater at the WTC a volumetric OUR setpoint of $22 \text{ mg/L}\cdot\text{h}$ resulted in an equilibrium SRT of about three days on an average basis. This setting provided treatment considered equal to the plant under automatic SRT control on an average basis. Table 21 summarizes the wasting activities for the pilot plant under OUR control for 2 October 1980. This table shows that wasting commenced at 0300 h as scheduled by the pilot plant operator on the minicomputer console and continued at half-hour intervals. The OUR set point of $22 \text{ mg/L}\cdot\text{h}$ was not reached by the end of this 24-hour period since waste sludge volume and duration constraints were exceeded at each wasting period (messages 13 and 14). DO was automatically controlled in each of the parallel plants to a value of 2 mg/L .

TABLE 21 PLANT WASTING SCHEDULE BASED ON OUR CONTROL,
OCTOBER 2, 1980

Time (h)	Volume Wasted (L)	System Mass (g)	Unintentional Waste (g)	Intentional Waste (g)	OUR (mg/L•h)	Scour (mg/g MLSS•h)	Message*
0300	50	5205	98	476	26	11.4	14
0330	100	5222	188	912	26	11.2	14
0400	140	5234	101	1220	26	11.0	14
0430	185	5241	103	1560	25	11.4	14
0500	229	5239	104	1865	24	11.8	13
0530	272	5232	105	2115	24	11.8	13
0600	312	5220	104	2330	23	12.0	13
0630	350	5205	106	2520	23	12.9	13
0700	386	5187	107	2700	23	13.0	13
0730	421	5146	108	2850	22	12.6	13
Instantaneous Equilibrium Set Point	SRT = 1.74 d SRT = 2.66 d OUR = 22.00 mg/L•h						

* Message 13 indicates duration constraint exceeded; message 14 indicates volume constraint exceeded.

Figure 42 shows the calculated OUR results for the 24-h period on 2 October 1980. Peak hydraulic and organic loading occurred at approximately 2000 h. Peak OUR corresponded with the peak loading due to increased microbial activity for cell synthesis and oxidative respiration. After 0300 h, as sludge wasting commenced, the OUR can be seen to decrease at an approximately constant rate coinciding with the rate of sludge wastage as indicated in Table 21. The desired OUR set point of 22 mg/L•h was not met in the time or wasting constraints allocated for the particular loading conditions to the plant. The final OUR in the 24-h period occurred at 0730 h having a value of 22.85 mg/L•h. It can also be seen that the instantaneous SRT was only 1.74 d, indicating relatively high activity within the process with the result that maximum permissible sludge was wasted to reduce the activity as measured by OUR. Typically, high loadings and activity were observed during the mid-week days, leading to increased wasting and decreased instantaneous SRT's. The data shown in Figure 42 was for a Thursday run (2

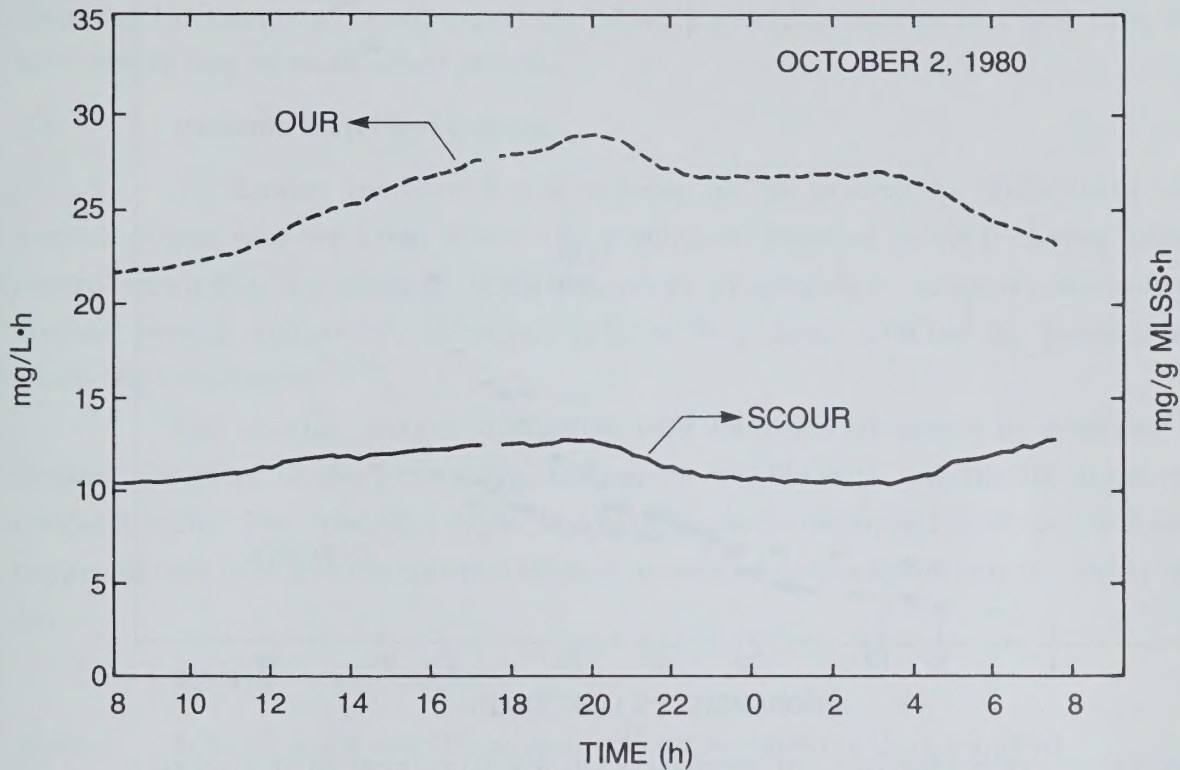


FIGURE 42 OXYGEN UPTAKE RATE AND SPECIFIC OXYGEN UPTAKE RATE, OCTOBER 2, 1980

October 1980). The instantaneous SRT in the parallel system was three days. Conversely, due to decreased weekend loadings to the plant and resultant decreases in OUR, less sludge was wasted from the plant under OUR control than from the plant under automatic SRT control on the weekends.

Figure 43 summarizes the probability distribution of the instantaneous SRT values for each plant throughout the period of OUR control. The median SRT's were approximately equal with a value of about 3.5 days for the OUR-controlled plant and 3 days for the SRT-controlled plant; however, the SRT of the OUR-controlled system varied significantly. The data showed that the instantaneous SRT of the OUR-controlled plant had a weekly cycle with high values usually occurring on the weekends. This coincided with low organic loadings to the plant. Decreases in OUR through decreased respiration resulted in less waste sludge from the OUR-controlled plant during low loading periods and more waste sludge at high organic loadings. As indicated by several authors,

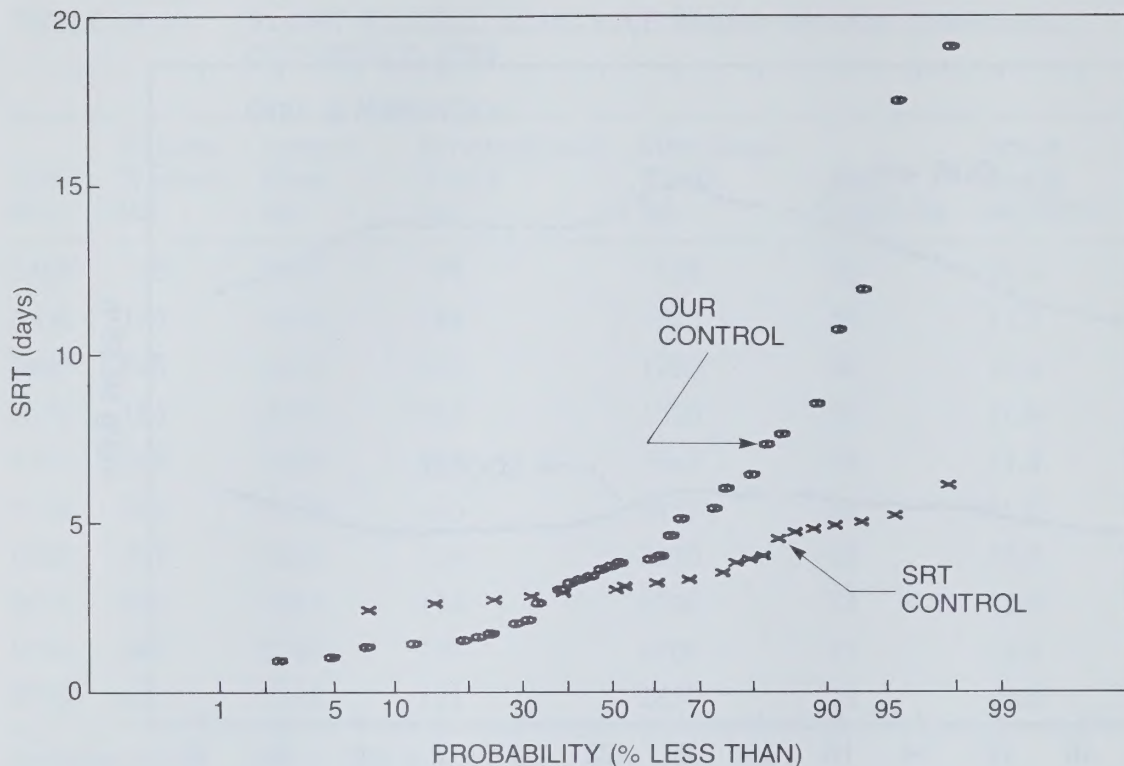


FIGURE 43 DISTRIBUTION OF INSTANTANEOUS SRT's FOR OUR AND SRT CONTROLLED PLANTS

the OUR is an effective indicator of microbial activity and growth and can be monitored with existing DO and air flow analyzers.

A slight improvement in mean effluent suspended solids was observed in the OUR-controlled plant compared to the SRT-controlled plant based on paired data (Table 19). Further data would be required to convincingly indicate a real difference in effluent SS over a long period.

Although the difference in mean SVI's was not significant during the OUR control period, the SRT-controlled plant had a variation and peak in SVI significantly higher than the OUR-controlled plant's SVI. An insufficient period was studied to determine whether the sludge inventory control strategies significantly influenced the SVI's of each plant.

More work would be necessary to fully evaluate the significance of sludge inventory control based on oxygen consumption, but the strategy is technically feasible and effectively reduces variations in microbial activity as measured by OUR. Future

work should be directed toward recursive estimation of the process $K_L a$ and OUR as discussed by Holmberg³⁴. All experimental work should be carried out over time frames sufficiently long to verify observations.

5.4 Dynamic Step Feed Control

To dampen transient inputs imposed on the process by shock loads and the normal diurnal load variation within the constraints imposed by SRT control additional control strategies are needed. With the advent of affordable computer technology and on-line sensing equipment, increased efforts have been directed to development of short-term strategies^{35,36}.

The specific oxygen utilization rate (SCOUR) described by Andrews³⁷ is a dynamic indicator of sludge activity, the nature of pollutants, and the substrate reactor concentration. The specific oxygen utilization rate is dependent both on the biological oxygen uptake rate and the concentration of activated sludge in the reactor and is defined by:

$$\text{SCOUR} = \text{OUR}/X$$

where: SCOUR is the specific oxygen utilization rate ($\text{mg O}_2/\text{g MLSS}\cdot\text{h}$),

OUR is the volumetric oxygen uptake rate ($\text{mg O}_2/\text{L}\cdot\text{h}$), and

X is the MLSS concentration (g/L).

Control of SCOUR at a set point would provide a method of control for the activated sludge process exposed to transient loadings. A constant low value of SCOUR would indicate that the removal of influent organics is complete.

A multi-staged step feed system (Figure 44) can permit the manipulation of feed distribution to different points of the aerator causing the solids in the system to be redistributed between compartments over a short interval. Since SCOUR is dependent on the MLSS concentration as shown above, a set point SCOUR in the last compartment can be maintained by changing the influent contacting pattern. A constant SCOUR in the last compartment should control the effluent substrate concentration being discharged to the secondary settler.

5.4.1 Computer Simulations. It is not economically or physically feasible to test all alternative modifications or operating changes on full or pilot scale systems due to the long process response times characteristic of biological systems. A dynamic computer

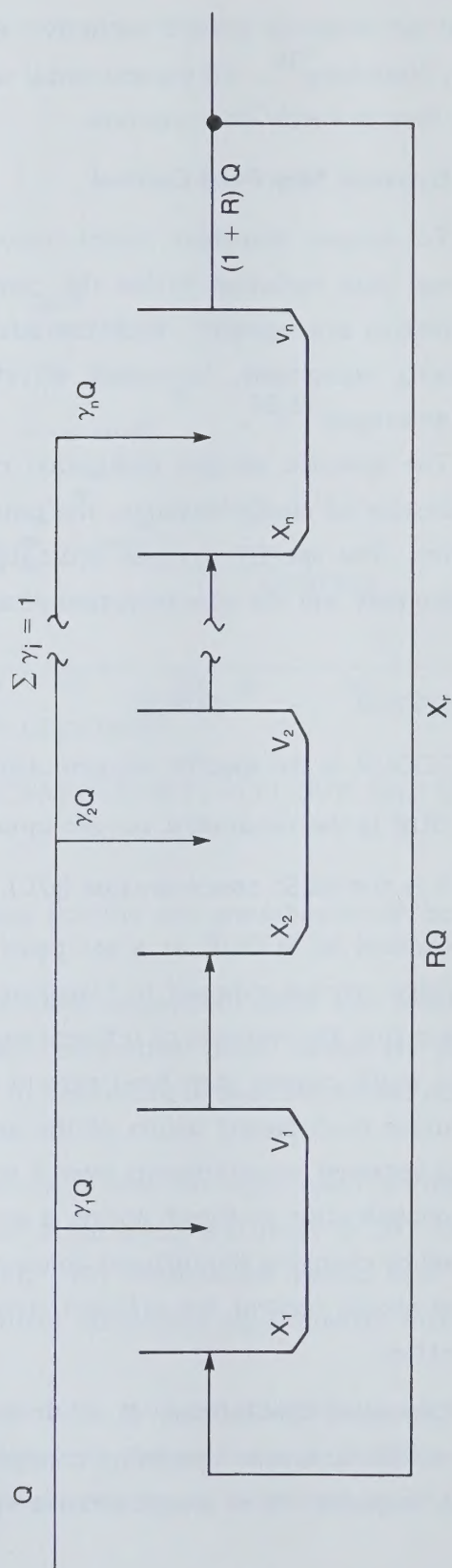


FIGURE 44 STEP FEED SCHEMATIC

simulation model describing the step feed modification of the activated sludge process was used to obtain a general understanding of process dynamics. This information was used to develop a dynamic control policy and an experimental design for the pilot scale system.

Computer simulation of the step feed process was used:

- a) to understand the dynamics of system solids distribution after a change was made in the influent contacting pattern,
- b) to determine if the last compartment's SCOUR of the step feed process level was directly related to the last compartment's substrate concentration,
- c) to determine the effect that a change in influent substrate concentration (step input) had on SCOUR and effluent substrate concentration, and
- e) to determine if biomass growth and decay kinetics should be considered in the controller design.

The microbial interactions and dynamics describing the aerator portion of the activated sludge process were proposed at Clemson University by Andrews and his co-workers^{38,39}. The model consisted of a sequential system of biological reactions as shown in Figure 45. Volatile concentrations of biomass in the aerator were subdivided into stored, active and inert (non-viable) fractions. This description of the biological reactor has been validated in the literature by Ekama and Marais⁴⁰, and Clifft and Andrews²².

One of the major shortcomings of modelling the activated sludge process has been inadequate representation of the clarification properties of the secondary settler, which in turn implies difficulty predicting effluent suspended solids concentrations. Because this simulation model was intended as a screening device, a simplified settler model was used. A mass balance was completed around the settler assuming constant effluent solids concentrations to estimate return sludge concentrations.

The option of operating N tanks in series with step feed influent distribution was included in the model (Figure 44). Simulated plant operating conditions were those anticipated for pilot plant application.

Steady-state conditions were reached for N compartments connected in series with the influent flow being distributed into the first compartment ($\alpha_1 = 1$); the influent flow was then transferred to the last compartment ($\alpha_N = 1$). Figures 46, 47 and 48 show the transient responses of MLSS concentrations, reactor substrate concentrations, and SCOUR levels for a three-compartment step feed system.

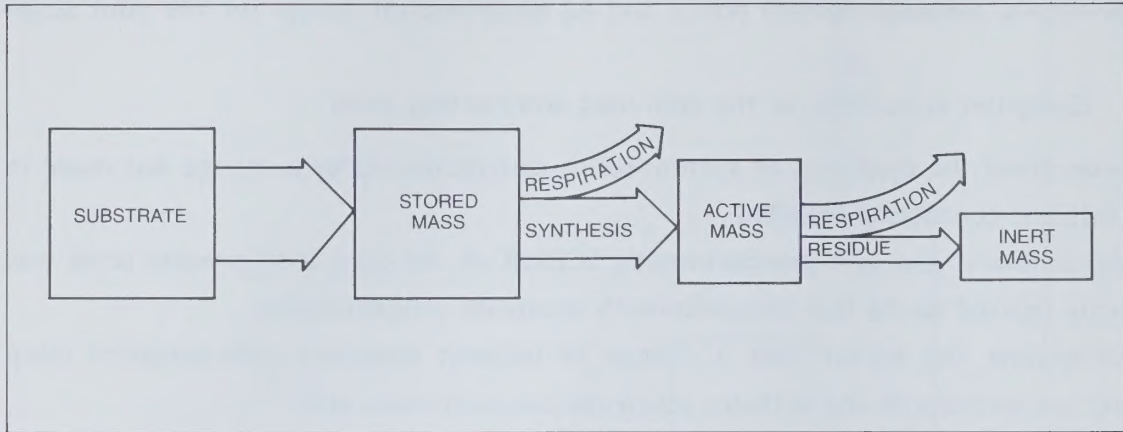


FIGURE 45 CLEMSON MODEL BIOLOGICAL REACTIONS²

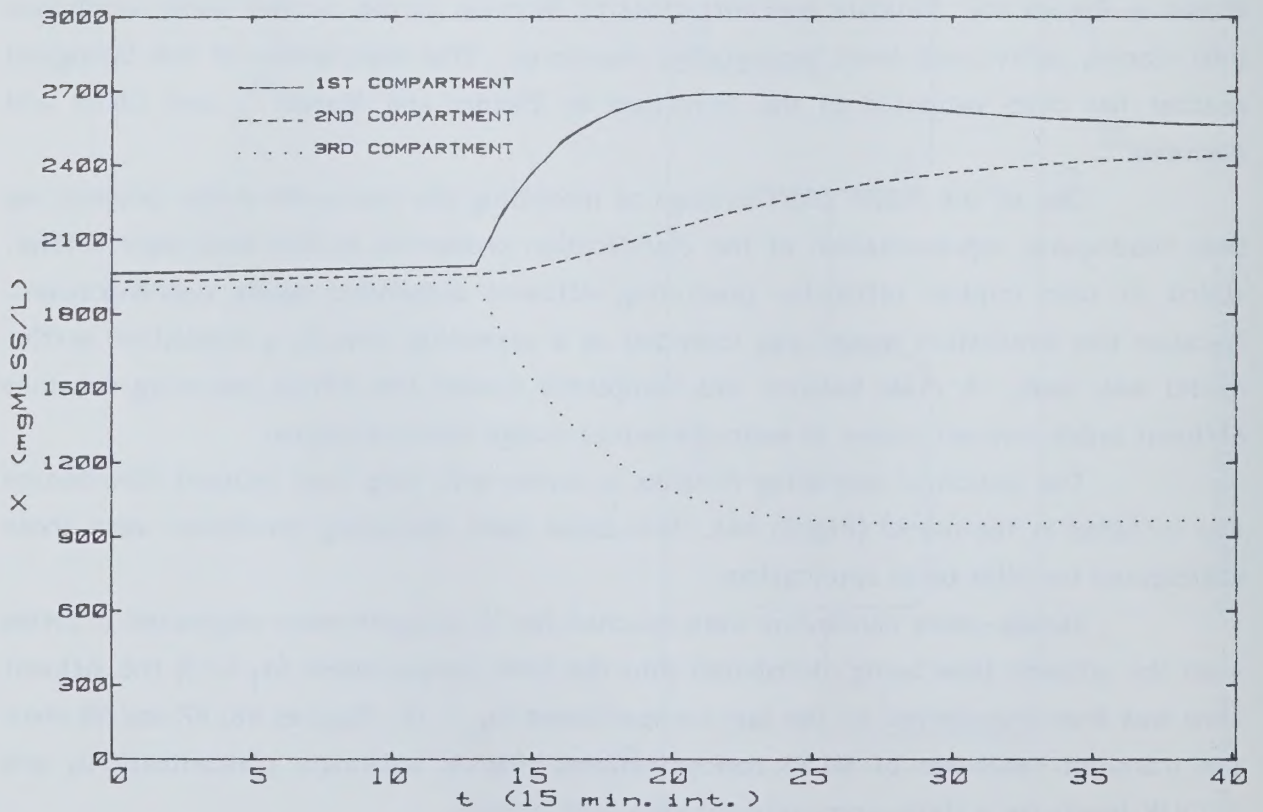


FIGURE 46 CLEMSON MODEL MLSS RESPONSE

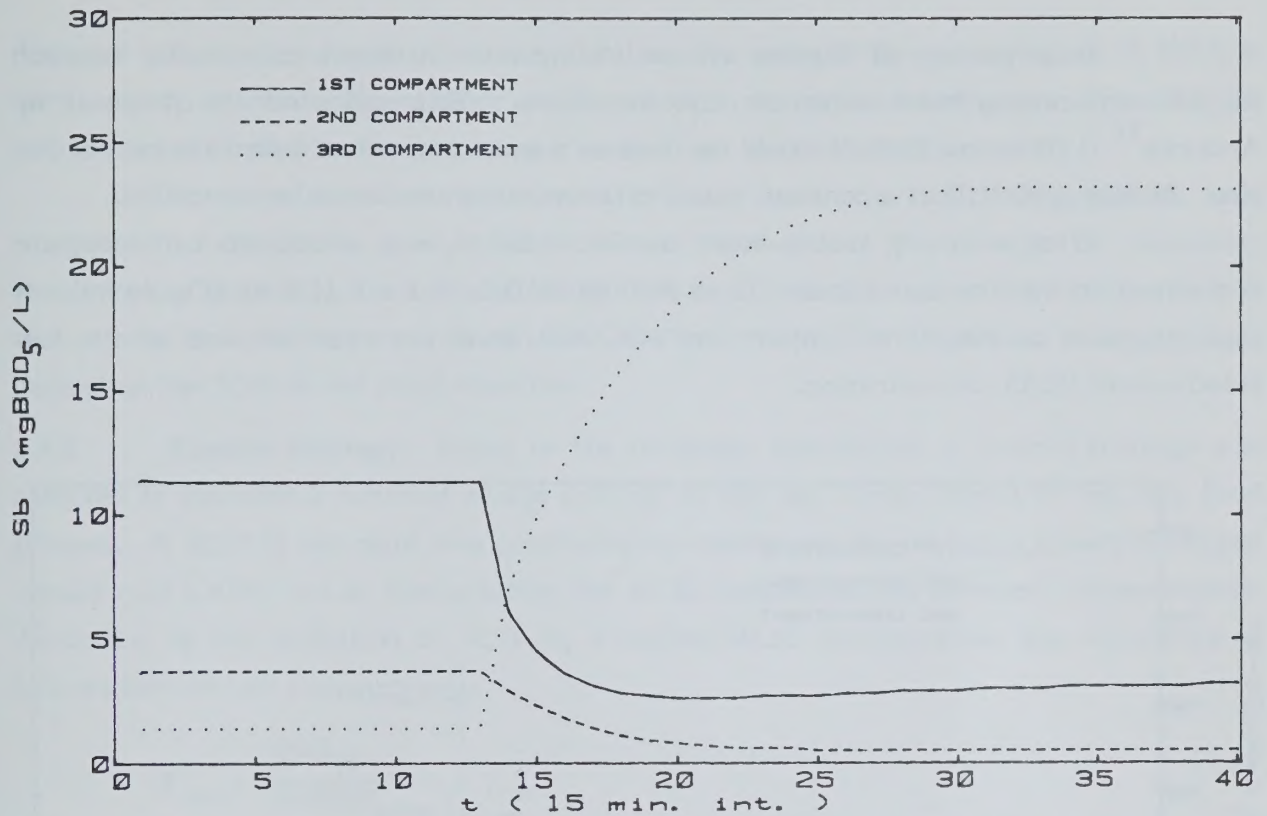


FIGURE 47 CLEMSON MODEL SUBSTRATE CONCENTRATION RESPONSE

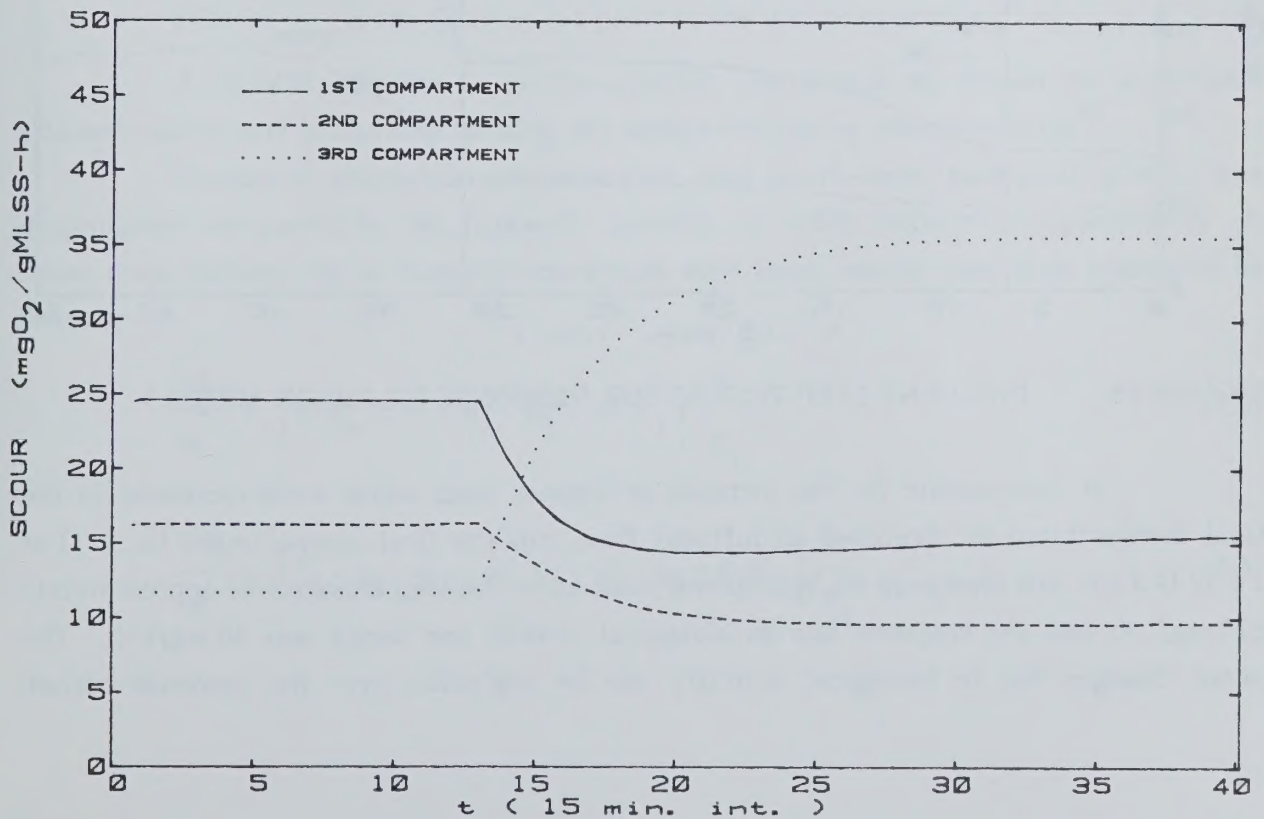


FIGURE 48 CLEMSON MODEL SCOUR RESPONSE

A comparison of Figures 47 and 48 indicated a direct relationship between SCOUR and compartment substrate concentrations. This validated the proposal by Andrews³⁷ (1977) that SCOUR could be used as a measurement of substrate concentration. By fixing SCOUR at a constant value, effluent substrate should be controlled.

After achieving steady-state conditions for $\alpha_3 = 1$, a step input of substrate concentration was simulated from 130 to 300 mg BOD/L at $t = 6$ (1.5 h), (Figure 49). A rapid increase in the third compartment's SCOUR level occurred because of the low steady-state MLSS concentration.

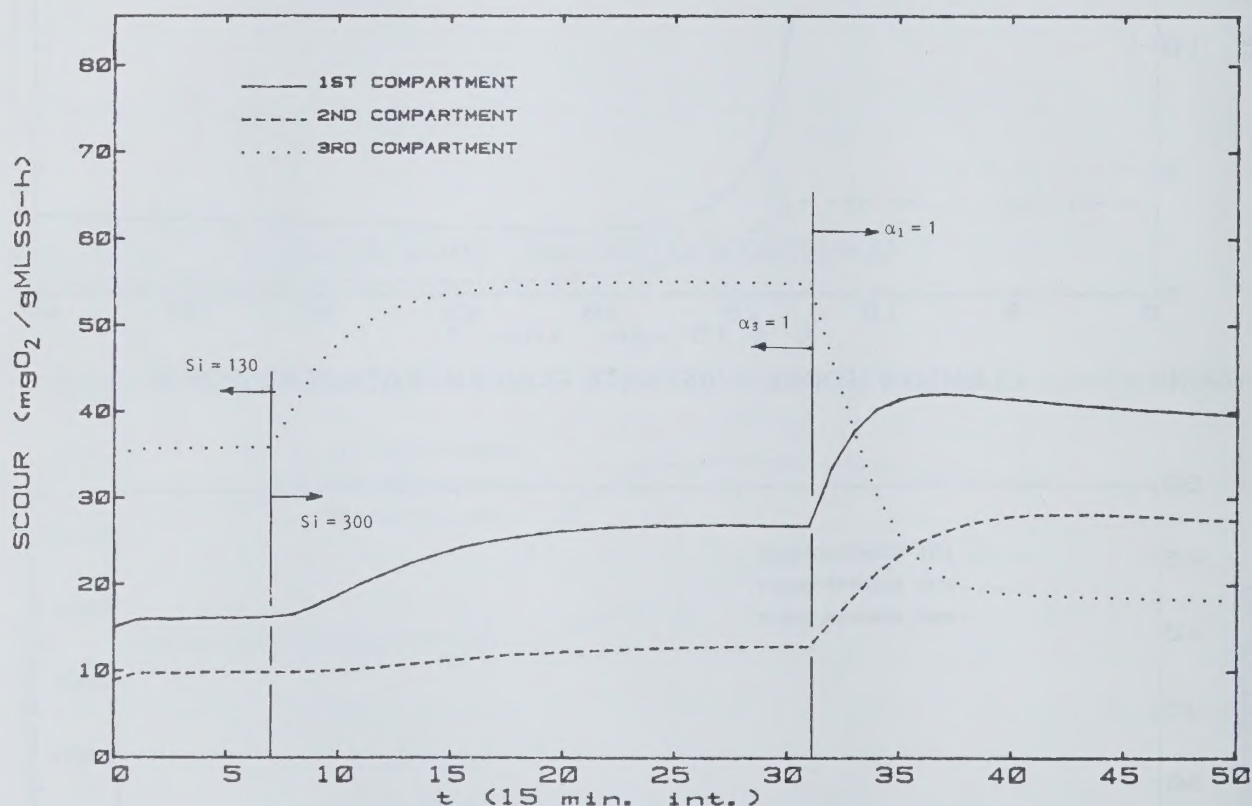


FIGURE 49 INFLUENT STEP TEST SCOUR RESPONSE (CLEMSON MODEL)

To compensate for the increase in organic load, solids were increased in the final compartment by directing all influent flow into the first compartment ($\alpha_1 = 1$) at $t = 32$ (7.7 h). The change in MLSS concentration after the step change was approximately $620 \text{ mg/L}\cdot\text{h}$ and the response due to biological growth and decay was $30 \text{ mg/L}\cdot\text{h}$. The minor changes due to biological activity can be neglected over the response period.

Effluent substrate transported to the clarifier was reduced by greater than 30 SCOUR units. MLSS response times were consistent with those observed previously when all influent was switched to the last compartment from the first compartment.

In response to an increase in influent load, the contacting pattern was readjusted to distribute more influent to the front end of the aerator for maximum treatment. Conversely, the influent would have been redistributed to the rear portion of the aerator if a decrease in influent load had occurred. The magnitude of change will depend on the SCOUR set point selection.

5.4.2 Control Strategy. Based on the computer simulations, a control strategy was selected to maintain a constant sludge activity in the last compartment of the step feed process. A SCOUR set point was controlled by monitoring the on-line volumetric oxygen uptake rate (OUR) and by manipulating the MLSS concentrations between compartments. According to the definition of SCOUR, a desired MLSS concentration was calculated as follows for the last compartment:

$$X_{des} = \frac{OUR_N}{SCOUR_{setp}} \quad (5.1)$$

where: X_{des} is the desired MLSS concentration in last compartment (mg/L),
 OUR_N is the volumetric uptake rate for last compartment (mg O_2 /L·h), and
 $SCOUR_{setp}$ is the SCOUR set point in the last compartment (mg O_2 /g MLSS·h).

A SCOUR setpoint is system-specific and should be chosen on acceptable effluent quality and favourable settling and sludge thickening characteristics³⁷.

Computer simulation demonstrated that short-term biological growth was insignificant compared to the hydraulic transfer of solids between compartments. A solids mass balance for a three-compartment step feed reactor was then expressed as follows:

$$\frac{dX_1}{dt} = \left[(RX_r - 1 - \alpha_2 - \alpha_3 + R) X_1 \right] \frac{Q}{V_1} \quad (5.2)$$

$$\frac{dX_2}{dt} = \left[(1 - \alpha_2 - \alpha_3 + R) X_1 - (1 - \alpha_3 + R) X_2 \right] \frac{Q}{V_2} \quad (5.3)$$

$$\frac{dX_3}{dt} = \left[(1 - \alpha_3 + R) X_2 - (1 + R) X_3 \right] \frac{Q}{V_3} \quad (5.4)$$

$$\alpha_1 = 1 - \alpha_2 - \alpha_3 \quad (5.5)$$

where: X_k is the MLSS concentration for compartment k (mg/L),
 V_k is the volume of compartment k (L),
 α_k is the flow distribution to compartment k (dimensionless),
 X_r is the return activated sludge concentration (mg/L),
 Q is the plant flow (L/h), and
 R is the recycle ratio (dimensionless).

These simultaneous differential equations were solved numerically using a fourth-order Runge Kutta routine. The integration interval was selected to equal 100 minutes. On-line sensors were used to measure the initial conditions required for integration.

The nonlinear method of Box⁴¹ was used to calculate optimal values of α_2 and α_3 that would minimize the function:

$$\text{Min } (X_{\text{des}} - X_3)^2 \quad (5.6)$$

Explicit and implicit inequality constraints used for the optimization were:

$$\alpha_2 \leq 1 \quad (5.7)$$

$$\alpha_3 \leq 1 \quad (5.8)$$

$$\alpha_2 + \alpha_3 \leq 1 \quad (5.9)$$

A 15-minute control interval was used to update the response trajectory for X_n . The instantaneous SCOUR response resulting from the control tended towards the selected SCOUR set point. This control approach was similar to that used by Richalet et al.⁴² in industrial plant applications.

5.4.3 Pilot Plant Operation. Pilot plant verification was carried out using the two pilot plants operated in parallel at the Wastewater Technology Centre. One system (Plant A) consisted of a three-compartment step feed process with recycle while the other system (Plant B) was a single-compartment completely mixed reactor with recycle.

A summary of the operating conditions used for both systems is given in Table 22. To maintain a constant average biological growth rate and to minimize nitrification,

TABLE 22 PILOT PLANT OPERATING CONDITIONS (Plants A and B)

Flow (L/h)	$480 + 146 \sin(2\pi t/24)$
Mean HRT (h)	4.6
Set point SRT (d)	3
F/M Ratio (mg BOD ₅ /g MLSS•d)	0.1 - 0.7
Recycle Ratio	0.5
Temperature (°C)	16
Setpoint DO (mg/L)	2-3

both plants were automatically controlled at a SRT of three days. Wastewater flow to both systems was controlled according to a 24-hour sinusoidal curve with peak flow coinciding with the period having maximum influent organic concentration. Temperature was controlled to approximately 16 °C and a recycle ratio of 0.5 was maintained. Air flow meters were installed for the B-system aerator and for the last compartment of the A system. Digital PI control algorithms were used to keep the dissolved oxygen levels at 2 mg/L with the exception of the last compartment of the controlled system which was kept at 3 mg/L.

Reaeration tests were performed on both the last compartment of the A system and the B system to estimate volumetric oxygen transfer coefficients ($K_L a$). Numerical estimates were obtained using non-linear least squares analysis. The air flow rate (AFR) and $K_L a$ were empirically related as shown in Figure 50. The volumetric oxygen uptake rate could then be calculated on-line from a mass balance around the reactor of concern.

For the step feed system, on-line OUR was calculated as follows:

$$OUR_k = K_L a (C_s - C_{o,k}) + (1 - \alpha_{k-1} + R) C_{o,k-1} - (1+R) C_{o,k} \quad Q/V_k$$

where: OUR_k is the volumetric oxygen uptake for reactor k (mg O₂/L•h),
 $K_L a$ is the volumetric oxygen mass transfer coefficient (h⁻¹),
 C_s is the saturation DO for wastewater (mg/L),
 $C_{o,k}$ is the controlled DO concentration for reactor k (mg/L), and
 α_{k-1} is the proportion of flow from the previous reactor.

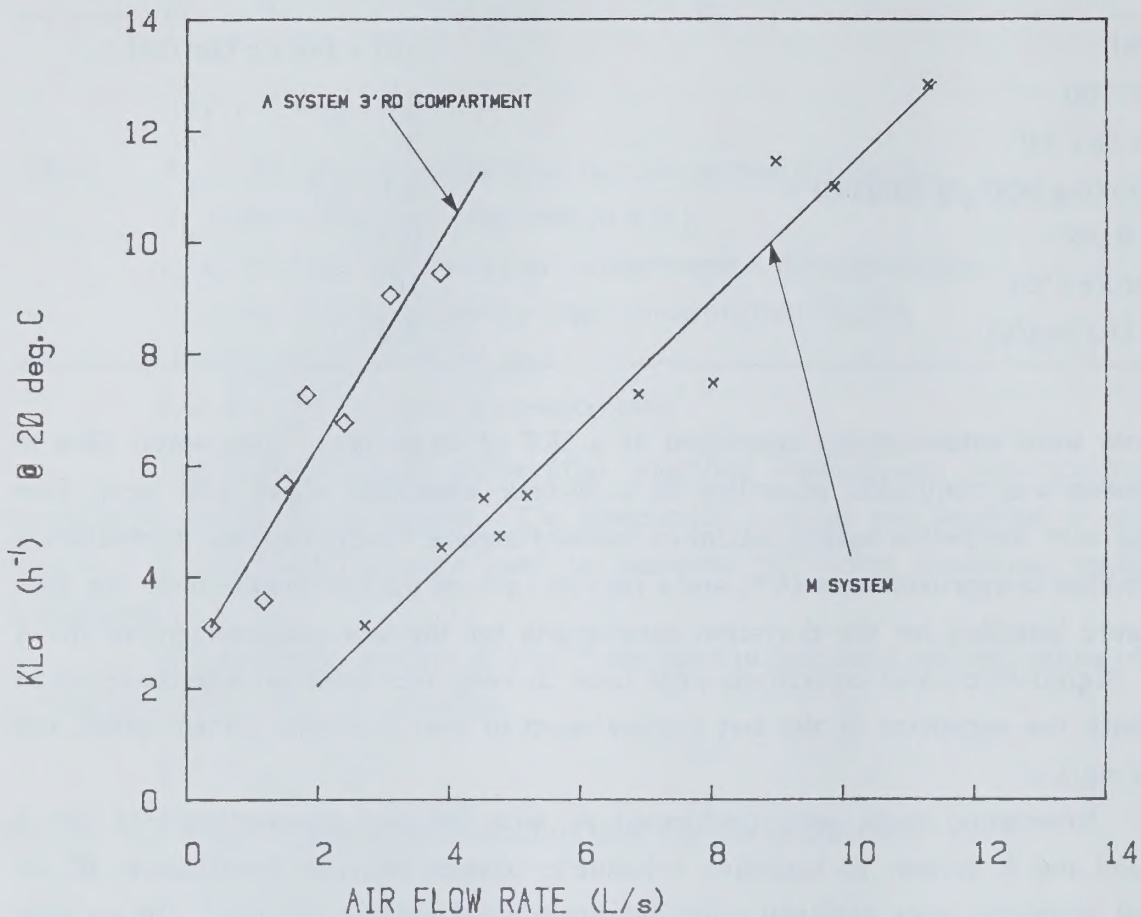


FIGURE 50 RELATIONSHIP BETWEEN $K_L a$ AND AIR FLOW RATE

5.4.4 Pilot Plant Control Results. Constant SCOUR control was initially applied to the A-system, optimizing influent flow to three compartments. The selected SCOUR set point was $15 \text{ mg O}_2/\text{g MLSS}\cdot\text{h}$. Unique minima did not exist for the objective function. The optimization selected a number of different α_2, α_3 combinations giving identical, instantaneous SCOUR values for the third compartment. Additional control constraints would be required to provide unique optimization for three-compartment distribution.

The control algorithm was subsequently modified to split the influent between only two compartments. The first and third compartments were used with the restriction that no influent would be added directly to the second compartment ($\alpha_2 = 0$). α_1 was calculated by difference ($\alpha_1 = 1 - \alpha_3$). A two-dimensional plot showing the relationship

between the objective function and percentage of flow to the last compartment is presented in Figure 51 for three loadings each having different OURs. Minimization of the objective function produced a unique minimum for each loading.

Six experimental runs were completed at different influent F/M loadings using two-compartment optimization. Table 23 summarizes discrete off-line samplings for Runs no. 2 to no. 7 using a SCOUR set point of 15 (mg O₂/g MLSS•h).

Figures 52 and 53 present instantaneous results for the A system operating under a steady F/M loading. The A system shows improved SCOUR control compared to the B system. The contacting pattern in Figure 53 was considered acceptable from a practical viewpoint.

Figures 54 and 55 present instantaneous control results with highly variable influent loadings. The A-system showed improved control during high loading periods when more influent was distributed to the first compartment. Conversely, influent was distributed largely to the last compartment under lower loading conditions at hour 8. During low loadings, the control was restricted as all the influent was being distributed to the final compartment.

Table 24 presents pooled results after separating data into runs having high and low loading conditions. Filterable organic carbon effluent data (EFOC) suggested that a reduced effluent variability can be obtained from the SCOUR control proposed during high loadings. At low loadings, where SCOUR control is limited, no improvement of instantaneous SCOUR or EFOC variability would be expected in comparison to the B-system. Consistently higher effluent suspended solids concentrations (ESS) were observed in all experiments with the controlled system. Before SCOUR control could be evaluated fully, the problem of increased effluent suspended solids concentrations had to be addressed.

Oxygen transfer efficiencies calculated for both pilot systems showed that both plants had efficiencies of less than one percent. Typical transfer efficiencies for coarse-bubble aeration systems are reported in the literature as being between 4 and 8 percent⁴³. Because of this inefficiency, excess air flow rates were applied. The Ontario Ministry of the Environment⁴⁴ recommends a value of $3.3 \times 10^{-3} \text{ m}^3/\text{m}^3 \cdot \text{s}$. The aeration mixing levels for the A system's third compartment while operating at a DO set point of 3 mg/L exceeded the guideline by a factor of 8. This mixing level would decrease if the DO set point was lower or the oxygen transfer efficiency was higher. These high air flow rates may have adversely affected the biomass flocculation performance which in turn can affect the effluent suspended solids concentrations⁴⁵.

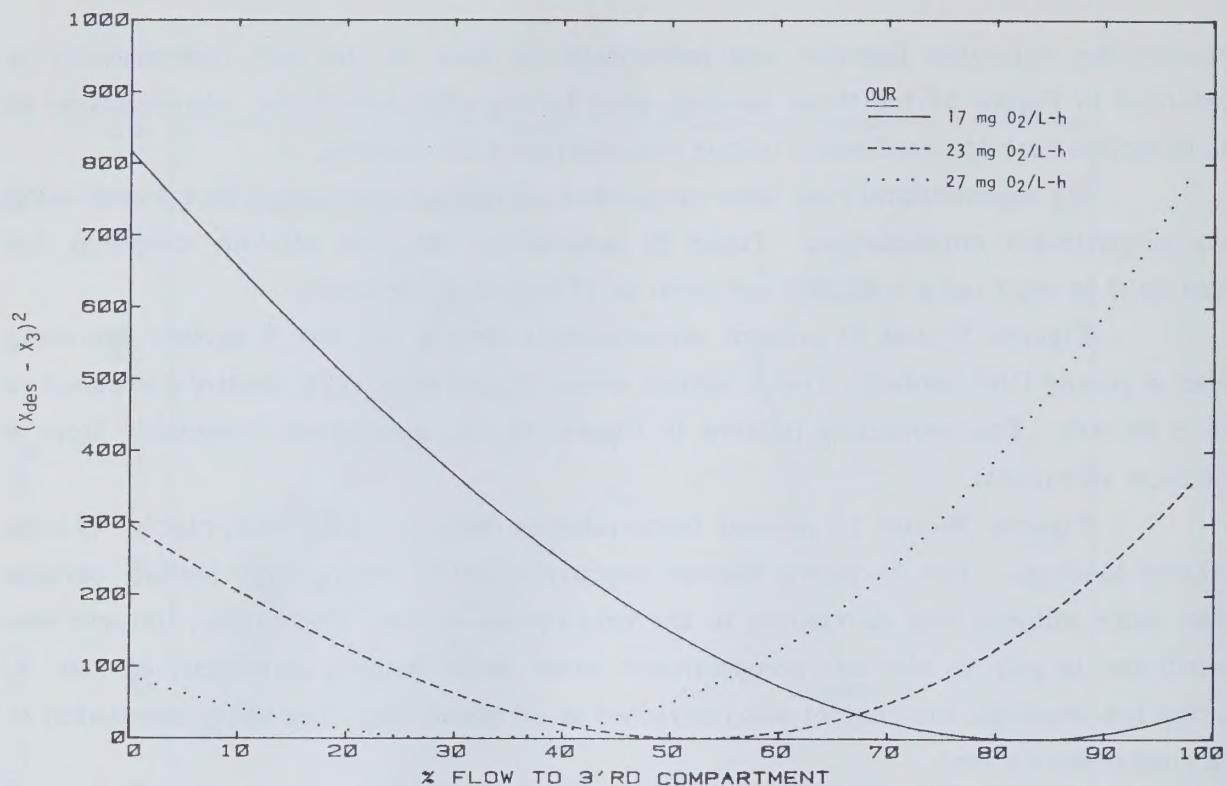


FIGURE 51 TWO-COMPARTMENT OPTIMIZATION

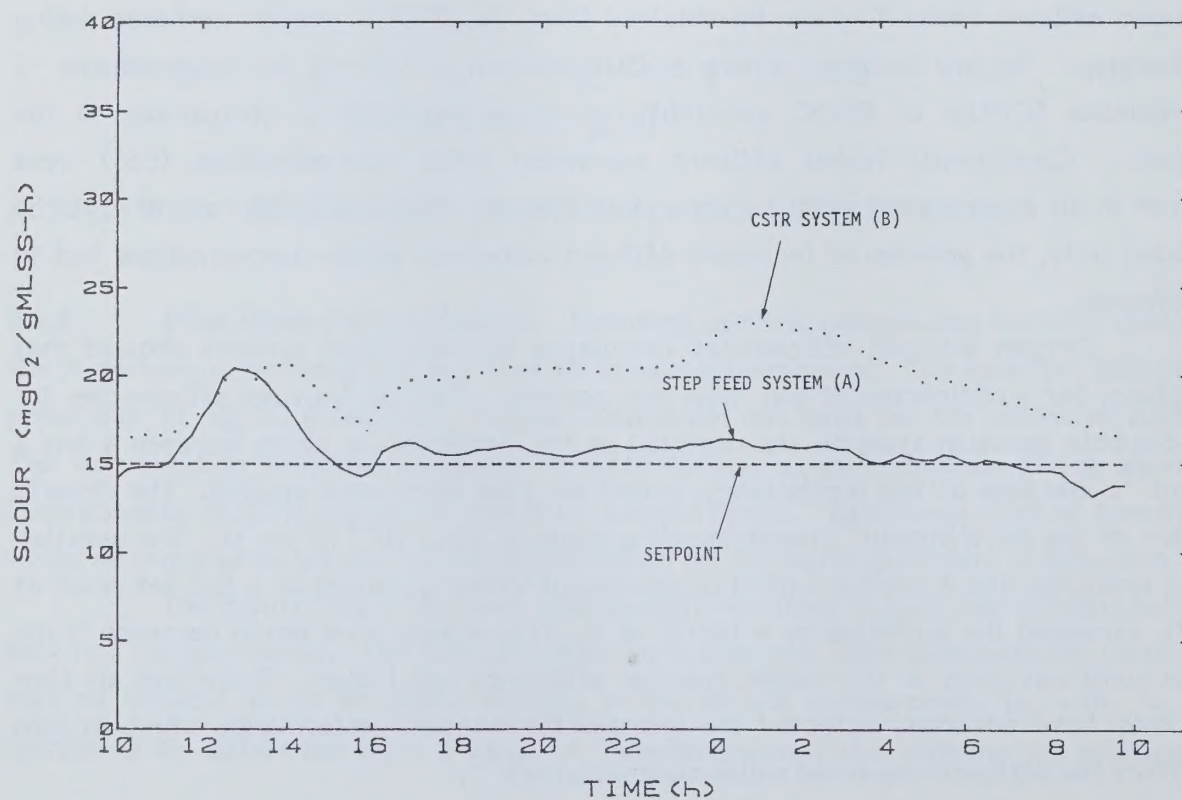


FIGURE 52 TWO-COMPARTMENT SCOUR CONTROL (HIGH LOADING)

TABLE 23 DYNAMIC STEP FEED PROCESS CONTROL RESULTS (SCOUR SETPOINT = 15 mg O₂/g MLSS•h)

		Mean ± Standard Deviation									
Run	Duration (h)	Influent Loading (g BOD ₅ /g MLSS•d)	Actual Continuous SCOUR (mg O ₂ /g MLSS•h)		EFOC** Effluent (mg/L)		ESS** (mg/L)		N	B	N
			A	B	A	B	A	B			
Run 1*	27	0.5	15.6 ± 0.8	17.7 ± 4.7	17 ± 5	17 ± 6	42 ± 11	29 ± 11	16	6	5
Run 2	24	0.7	14.9 ± 1.5	18.9 ± 4.2	17 ± 2	18 ± 4	41 ± 9	25 ± 5	25	4	8
Run 3	24	0.1	12.7 ± 2.8	14.4 ± 2.1	18 ± 3	15 ± 2	40 ± 12	20 ± 5	25	2	7
Run 4	24	0.1	14.2 ± 2.2	15.5 ± 2.5	17 ± 4	17 ± 2	28 ± 8	19 ± 5	25	2	8
Run 5	24	0.7	14.3 ± 2.3	21.8 ± 4.3	26 ± 5	28 ± 6	28 ± 5	23 ± 5	25	6	9
Run 6	19	0.3	15.5 ± 0.5	20.9 ± 2.4	19 ± 2	18 ± 1	31 ± 18	16 ± 9	17	1	7
Run 7	24	0.4	15.8 ± 1.4	19.7 ± 1.8	20 ± 5	23 ± 7	22 ± 6	12 ± 3	25	7	9

* Three-compartment optimization. All other runs were with two compartments.

** Underlined means and standard deviations indicate differences between A and B were determined to be statistically significant.

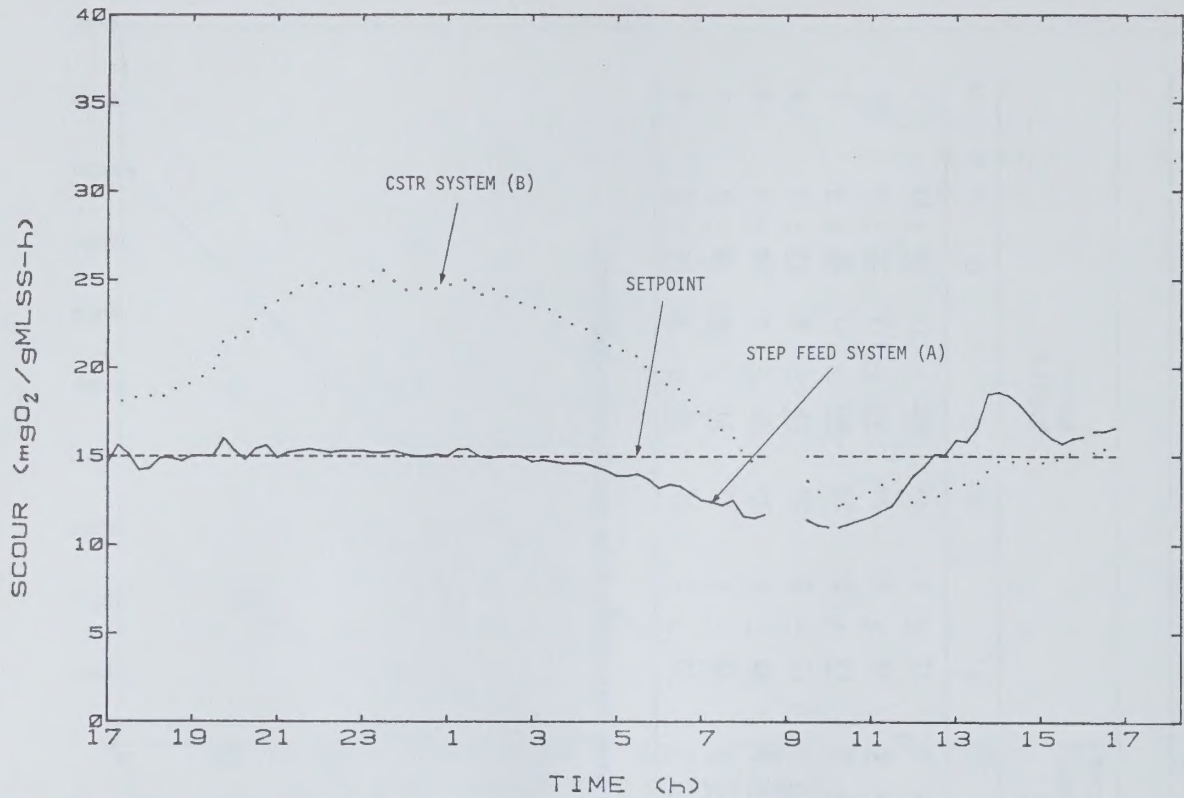


FIGURE 53 TWO-COMPARTMENT SCOUR CONTROL (HIGH LOADING)

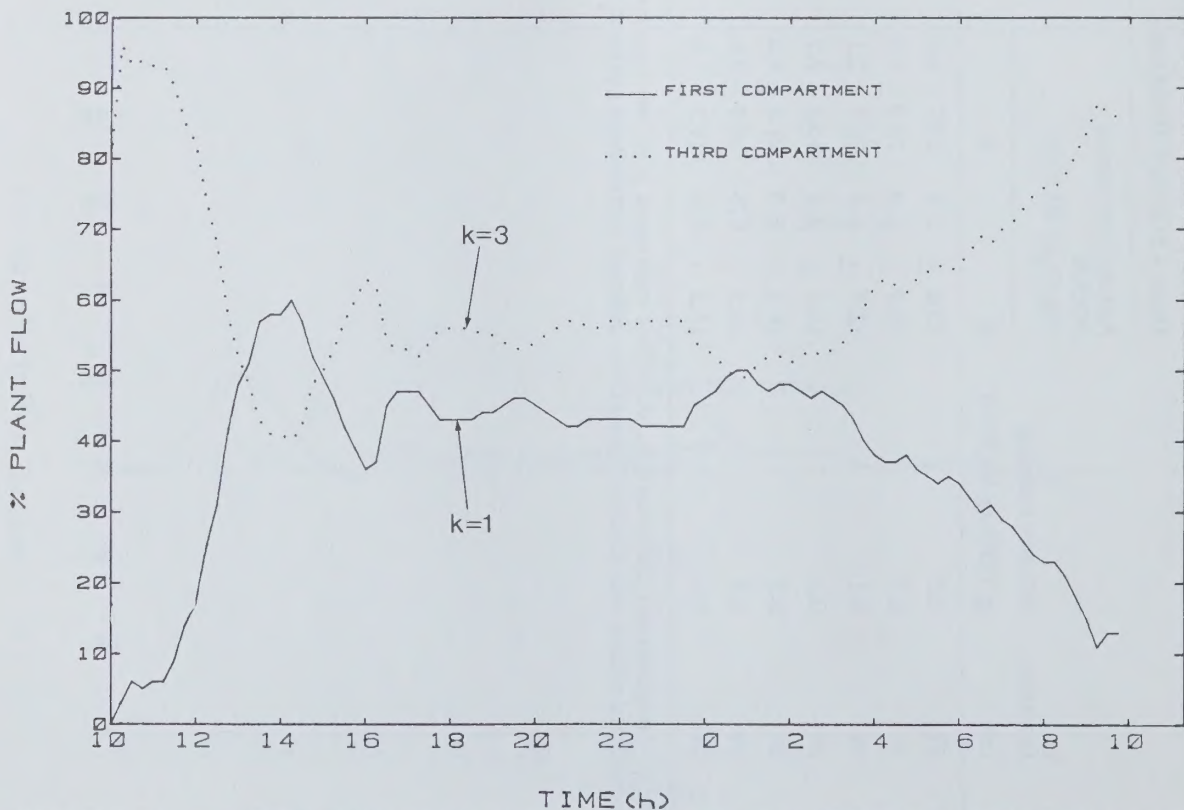


FIGURE 54 TWO-COMPARTMENT CONTACTING PATTERN (VARIABLE LOADING)

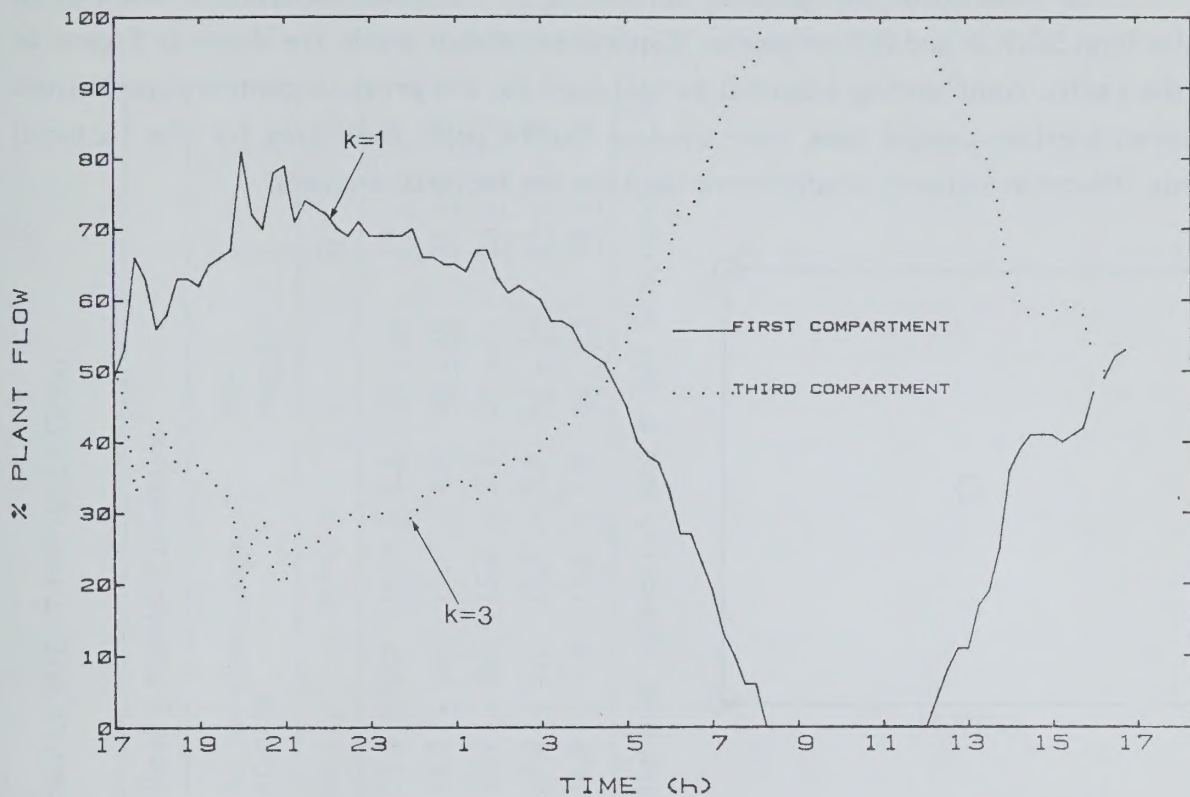


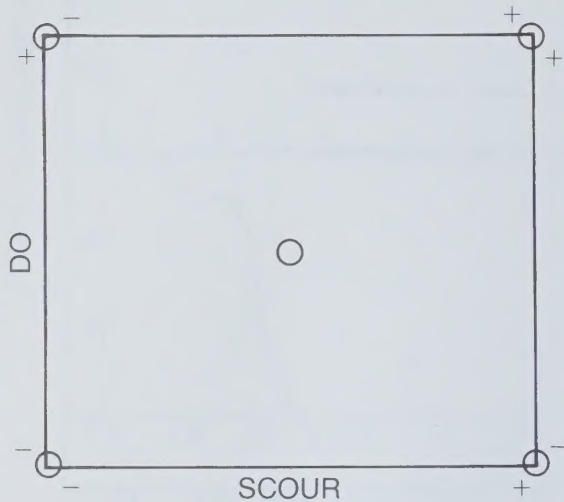
FIGURE 55 TWO-COMPARTMENT CONTACTING PATTERN (VARIABLE LOADING)

TABLE 24 PARALLEL PLANT COMPARISONS (SCOUR Setpoint = 15 mg O_2 /g MLSS•h)

Mean Load*	CONTINUOUS SCOUR (mg O_2 /g MLSS•h)		EFOC (mg/L)		ESS (mg/L)	
	A	B	A	B	A	B
0.6	15.0 $\pm$ 1.8	20.1 $\pm$ 3.9	21 $\pm$ 4	23 $\pm$ 6	30 $\pm$ 7	20 $\pm$ 4
0.2	14.1 $\pm$ 2.1	16.9 $\pm$ 2.3	18 $\pm$ 3	17 $\pm$ 2	33 $\pm$ 13	18 $\pm$ 7

* (g BOD₅/g MLSS•d)

To investigate the problem further, a 2^2 factorial experiment was run to examine both SCOUR and DO set points. Experiment design levels are shown in Figure 56 with the centre point setting identical to that used for the previous control experiments. The seven previous control runs were used as centre point replicates for the factorial analysis. Discrete effluent samples were used for the factorial analysis.



	-	+
SCOUR (mg/g MLSS·h)	11	19
DO (mg/L)	1	5

FIGURE 56 FACTORIAL DESIGN SETTINGS

Linear regression was used to statistically analyze the factorial results⁴⁶. Table 25 presents continuous SCOUR and discrete effluent results from the factorial experiment.

The dissolved oxygen set point had the largest effect on both the ESS concentrations. Further details on the factorial statistical analysis can be found elsewhere⁴⁷. An increase in air flow probably affected the settling characteristics of the bio-floc.

TABLE 25 FACTORIAL CONTROL RESULTS (TWO-COMPARTMENT OPTIMIZATION)

Influent Loading (g BOD ₅ /g MLSS•d)		A-System Set points		Mean ± Standard Deviation *			
				Actual Continuous SCOUR		ESS (mg/L)	
		DO (mg/L)	SCOUR (mg O ₂ /g MLSS•h)	A	B**	A	B N
Run 8	0.3	5	11	11.0 ± 0.2	11.7 ± 1.8	<u>53 ± 14</u>	<u>19 ± 7</u> 9
Run 9	0.6	5	19	18.7 ± 1.5	15.4 ± 2.7	<u>69 ± 34</u>	<u>26 ± 6</u> 9
Run 10	0.4	1	11	12.1 ± 0.9	16.8 ± 2.9	<u>25 ± 7</u>	<u>20 ± 7</u> 8
Run 11	0.2	1	19	18.8 ± 1.1	13.7 ± 2.5	<u>43 ± 14</u>	<u>14 ± 3</u> 8
Run 12	0.3	3	15	14.8 ± 1.5	11.8 ± 2.4	<u>34 ± 13</u>	<u>18 ± 4</u> 9

* Underlined means and standard deviations indicate difference between A and B was determined to be statistically significant.

** The B-system had 2.0 mg/L DO set point for all runs.

Based on the evidence presented from the factorial experiment and after examining the pilot plant's aeration system, one can conclude that the increase in ESS for the A system was mainly due to excess air flow rates in the last compartment. The air flow rate to the reactor was dependent on the dissolved oxygen set point.

5.4.5 Improving SCOUR Process Control. Pilot plant results had indicated that SCOUR control was limited under low influent loading conditions due to the limitations imposed by hydraulic factors ($\alpha_3 = 1$). The recycle ratio and/or final compartment volume adjustment could be decreased to increase the instantaneous SCOUR level when all influent was directed to the final compartment. The Clemson simulation model for the step feed system was used to examine these concepts. Simulated operating conditions were those used in pilot plant experimentation. All influent was distributed to the final compartment ($\alpha_3 = 1$) until steady-state conditions were attained. Tables 26 and 27 show steady state results after adjustments were made to the recycle ratio and final compartment volume. A substantial increase in SCOUR levels was observed. The simulated results confirmed the above concepts.

TABLE 26 RECYCLE EFFECTS ON SCOUR CONTROL LIMITS (CLEMSON MODEL)

Recycle Ratio (%)	SCOUR (third compartment) (mg O ₂ /mg MLSS•h)
100	12.6 - 28.4
80	12.2 - 30.6
50	11.8 - 35.8
20	11.1 - 48.2

Table 28 shows the effect on the SCOUR control range of baffling the aerator into separate sub-reactors. The lower limit was obtained by directing all influent to the first compartment until steady state was achieved. The upper limit is reached after redirecting all influent to the final compartment. The final compartment's control range had increased with the number of subreactors connected in series.

5.4.6 Summary of SCOUR Control Results. This pilot scale study demonstrated that dynamic on-line control of the specific utilization rate (SCOUR) can be achieved using the

TABLE 27 VARIABLE VOLUME EFFECTS ON SCOUR CONTROL LIMITS
(CLEMSON MODEL)

Third Compartment Volume (L)	SCOUR (third compartment) (mg O ₂ /mg MLSS•h)
733	11.8 - 35.8
700	11.9 - 36.2
650	12.0 - 36.9
600	12.4 - 38.4
400	13.1 - 40.3

TABLE 28 NUMBER OF REACTORS IN SERIES EFFECT ON SCOUR CONTROL
LIMITS (Total Volume = 2200 L)

Number of Reactors	SCOUR Range (third compartment) (mg O ₂ /g MLSS•h)
2	13.3 - 30.1
3	11.8 - 35.8
4	11.0 - 38.6

step feed process. Step feed capability resulted in less variation in SCOUR than was observed in a parallel single-tank completely mixed process. During low organic loading periods SCOUR control was limited due to constraints imposed by hydraulic factors. Continuous optimal contacting patterns were calculated and applied to the first and third compartments of a step feed pilot plant system. Additional constraints to the SCOUR control presented would be required to provide unique optimization for influent distribution to three or more compartments.

Off-line effluent filterable organic carbon (EFOC) data suggested that a reduced effluent variability was obtained from the SCOUR control strategy during high organic loading periods. No improvement in either EFOC or effluent suspended solids (ESS) was obtained during periods of low influent loading. The high ESS concentrations observed for the controlled step feed system were attributed to excess air flow rates caused by the inefficient oxygen transfer of the pilot aeration system and the DO set point in the final compartment.

6 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations regarding improvements in activated sludge operation that result from the application of instrumentation and automatic control are presented in two parts.

6.1 Instrumentation

- 1) Acceptable instruments exist which can enhance the monitoring of key variables within the activated sludge process. Instruments evaluated within this study and found to give acceptable results included sensors for: flow rate, dissolved oxygen, mixed liquor suspended solids, return and waste activated sludge suspended solids, temperature, and pH. A low level of precision was found in the instrument investigated for measuring effluent suspended solids by photometric analysis. A limited number of results using a self-cleaning instrument for the measurement of influent suspended solids indicated that acceptable results could be obtained. Operation of an on-line organic carbon analyzer required sample pretreatment by filtration and acidification to permit acceptable instrument performance. An average of 0.5-1.0 person-days per week of maintenance were required.
- 2) Adequate calibration and maintenance efforts must be provided to ensure satisfactory instrument performance. Requirements vary for each instrument type. It is essential to establish a routine maintenance and calibration programme for instruments, and to maintain a spare parts inventory for instrument repair.
- 3) The instrument accuracies and standard deviations were sufficient to permit their use for continuous automatic control.
- 4) Where possible, self-cleaning instruments should be considered for on-line use. If self-cleaning instruments are inappropriate, then the use of high-shear field should be considered (e.g. flow-through configurations) to minimize bio-film development on sensor surfaces.
- 5) Improved instruments without interaction between zero and span settings would be desirable to minimize the effort required for calibration adjustments.
- 6) Methods of on-line examination of instrument signal integrity need to be investigated to provide early warning systems of instrument failure.
- 7) Methods of on-line instrument calibration need to be investigated to reduce the instrument monitoring carried out by the plant operator.

- 8) The digital computer effectively summarized and displayed instrument-generated data from the process sensors. Graphical representation was a particularly informative method of examining the plant data.

6.2 Automatic Control

- 1) Energy savings are achievable through automatic dissolved oxygen control. It was measured that, on average, about 27% reduction in air applied to the pilot plant was achieved through automatic control. At full scale this saving would translate directly to energy savings. Actual energy savings would be site specific and depend upon existing plant design, configuration and plant loading characteristics.
- 2) The use of automatic dissolved oxygen control appeared to lead to improved sludge settleability as measured by SVI compared to the manually controlled pilot system. No improvement in effluent quality could be attributed to automatic control at the pilot plant level.
- 3) Effective control of activated sludge solids inventory was accomplished through the use of on-line process analyzers for flow and suspended solids interfaced to a microprocessor or minicomputer. The merits of automated solids inventory need to be evaluated on a full scale plant.
- 4) The on-line monitoring of the in situ respiration rate using the aforementioned instrumentation can permit the automatic control of the plant solids inventory. More investigation needs to be performed to determine the overall advantages and disadvantages of this approach to solids inventory control. Recursive methods of updating the oxygen transfer coefficient need to be investigated.
- 5) The on-line measurement of the specific oxygen utilization rate provided for the dynamic control of feed distribution in a step feed system. Variations in the specific oxygen utilization rate were minimized in the final stage of the step feed system. Effluent filterable organic concentration variations were minimized in the dynamic step feed system.
- 6) As shown in the dynamic step feed system, the aeration efficiency appears to have a significant effect upon effluent suspended solids concentration.

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Mr. R.G. Gillespie took responsibility for construction and upkeep of the pilot plant and control hardware. The advice and efforts of these two members of the WTC's staff was greatly appreciated.

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